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SKILL REPRODUCTION IN A REDUCED TIME-FRAME BY MARTIAL ATHLETES

by

Andy Roosen

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

October 2007

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Abstract

Skill reproduction in a reduced time-frame by martial athletes
Andy Roosen, Loughborough University, 2007

Taekwondo (TKD) and karate are martial sports which require athletes to reproduce whole-body complex skills in reduced time-frames during competition. It is important to determine whether differences exist between training 'maximum' (normal) and competition 'maximum' (100%) modes of execution of a movement combination, to ensure training executions adequately and specifically reflect those in competition.

Three-dimensional analyses of five athletes from each sport were conducted. Kinematic differences between execution modes were measured and the kinetic causes for these differences were investigated and related to the motor control involved in these martial arts combinations. The analysis used a fourteen-segment representation of the martial athlete, incorporating both functional and predictive joint centres and subject specific inertia data, and was designed to best represent the explosive movements observed in both sports.

The study showed that athletes lowered the execution times of their combinations in 100% mode, but did so using different strategies. If contact velocities of a technique increased this was achieved by increasing the peak velocity alone, if it decreased this was due to a lower peak velocity and a different deceleration pattern. The striking limb showed few angle differences at target contact between execution modes. More angle differences were observed for central segments which appeared to be related to controlling the effective mass of a technique and the athletes attempting to reduce the transfer time between techniques of the combination in 100% mode. The striking limbs demonstrated low variability in joint moments, while more moment variability was observed for other joints, particularly in the central segments. Joint moments were more variable in 100% mode even though their trends and joint angle regularity were maintained. This variability in moments may be required to keep the movement on track. TKD athletes did not optimise their kicks for maximal impact when kicking the training target pads. Karate athletes controlled energy transfer to the target when attacking the head through controlling effective mass and the moment sequencing of the striking limb, rather than velocity.

Practical implications of the study were: TKD athletes should include combination training on heavy targets; combinations can be improved by focussing on the initial and transfer phases; and strengthening central and support segments may reduce chronic injury.
Publications

Conference presentations and published abstracts


Reports

Acknowledgements

Martial arts have been a major part of my life and being able to do academic research into something that means so much to me has been a real privilege. I am very grateful for the guidance, encouragement and friendship of my supervisor, Dr Matthew Pain. I consider myself truly lucky to have been able to do this research under the supervision of a fellow martial artist.

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But most importantly, I would like to thank my wife Manu, for encouraging me and brightening up my life! Without her none of this would have been possible. To her I dedicate this work.
Dedication

To my wife Manumatavai:
Thank you for your support, encouragement and love.

'Ofa lahi atu
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<tr>
<td>100% mode</td>
<td>execution mode representing a competition maximum execution</td>
</tr>
<tr>
<td>2D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>$\partial U$</td>
<td>partial derivative of $U$</td>
</tr>
<tr>
<td>aCW</td>
<td>anti clockwise</td>
</tr>
<tr>
<td>ApEn</td>
<td>approximate entropy</td>
</tr>
<tr>
<td>CoM</td>
<td>centre of mass</td>
</tr>
<tr>
<td>CoR</td>
<td>centre of rotation</td>
</tr>
<tr>
<td>CW</td>
<td>clockwise</td>
</tr>
<tr>
<td>DoF</td>
<td>degrees of freedom</td>
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<tr>
<td>Eq.</td>
<td>equation</td>
</tr>
<tr>
<td>GMP</td>
<td>generalised motor program</td>
</tr>
<tr>
<td>HA</td>
<td>helical axis</td>
</tr>
<tr>
<td>ICR</td>
<td>instant centre of rotation</td>
</tr>
<tr>
<td>IOC</td>
<td>International Olympic Committee</td>
</tr>
<tr>
<td>JC</td>
<td>joint centre</td>
</tr>
<tr>
<td>K</td>
<td>kinematic difference</td>
</tr>
<tr>
<td>K1, K2, K3</td>
<td>Kicks 1, 2 and 3 of the TKD combination</td>
</tr>
<tr>
<td>Karateka</td>
<td>karate practitioner</td>
</tr>
<tr>
<td>Kk</td>
<td>Kick of the karate combination</td>
</tr>
<tr>
<td>LED</td>
<td>light emitting diode</td>
</tr>
<tr>
<td>MoI</td>
<td>moment of inertia</td>
</tr>
<tr>
<td>MSE</td>
<td>mean square error</td>
</tr>
<tr>
<td>Normal mode</td>
<td>execution mode representing a training maximum execution</td>
</tr>
<tr>
<td>P1, P2</td>
<td>punches 1 and 2 of the karate combination</td>
</tr>
<tr>
<td>Pseudo force</td>
<td>readout in arbitrary units from force transducer in target pad</td>
</tr>
<tr>
<td>RoM</td>
<td>range of motion</td>
</tr>
<tr>
<td>S</td>
<td>statistically significant</td>
</tr>
<tr>
<td>SATO</td>
<td>speed-accuracy trade-off</td>
</tr>
<tr>
<td>SSC</td>
<td>stretch-shortening cycle</td>
</tr>
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<td>TKD</td>
<td>Taekwondo</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
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<td>--------------</td>
<td>-------------------------------</td>
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<tr>
<td>WKF</td>
<td>World Karate Federation</td>
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<tr>
<td>WSKA</td>
<td>World Shotokan Karate Association</td>
</tr>
<tr>
<td>WTF</td>
<td>World Taekwondo Federation</td>
</tr>
<tr>
<td>$\bar{x}$</td>
<td>vector x</td>
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<tr>
<td>$[X]$</td>
<td>matrix X</td>
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Chapter 1

INTRODUCTION

Skill reproduction has been widely studied and many theories for movement control have been proposed. The biomechanical analysis of sports techniques is also well represented in existing research. However, detailed three-dimensional (3D) analysis of whole-body complex movements for the purpose of skill reproduction has not been done previously presumably due to the complexity of its design and information processing. Such analysis requires knowledge and competency in both biomechanics and motor control. The fighting combinations used in taekwondo (TKD) and karate are excellent examples of complex movements that require a high level of coordination and control. Athletes use their fists and feet to score on their opponents whilst maintaining an appropriate body configuration to avoid being scored upon. Due to the explosive nature of both sports, athletes have very limited time-frames in which to execute these skilful combinations. Hence, the study of athletes from these two disciplines using 3D biomechanical tools is a novel endeavour analysing the reproduction of fast and complex sporting skills.

Traditional training methods in the martial arts typically enforce certain movement templates for techniques, i.e. coaches will insist on techniques being performed in a particular way and end positions of such techniques must conform to a certain template. These formalised executions are based on the experiences of previous masters and are often adopted as the sole way of performing the techniques correctly. Even in this modern world, coaches are reluctant to take into account the differences in anatomy and physiology of the athletes and acknowledge the progresses made in movement and sports science, which could have a marked effect on the performance of these techniques. Therefore, athletes are discouraged from exploring and varying techniques to find an execution that best suits them. By analysing whether elite athletes alter the reproduction of a combination for competition conditions and determining what the variability in such executions may be, this study investigates whether the execution of these skills should be allowed more freedom and whether variability in learning skills, rather than the traditional restriction, may lead to a more robust skill execution.
1.1 The global spread of martial arts

The term 'martial arts' literally means arts of war and hence applies to soldiery and combat systems practised by any culture. However, the term more commonly refers specifically to the oriental martial arts. Martial arts are typically defined as systems 'of combat and self-defence [...] developed especially in Japan and Korea and now usually practised as a sport' (Encarta World English Dictionary, 2007). The origins of the oriental martial arts are shrouded in myth and legend (Funakoshi, 1973; Finn, 1988; McCarthy, 1996). Their global exposure, however, goes hand in hand with the interactions between nations of the orient and the occident. The earliest interactions can be attributed to the establishment of trade links by Alexander the Great towards the end of the 4th century BC (Finn, 1988) and trade routes such as for silk which reached from the Black Sea to the north of China were catalysts for the spread of knowledge. These trade routes were often treacherous, and traders would seek ways to protect themselves either by self-learning or by hiring bodyguards. As trade and knowledge spread between Europe and Asia, so did the self-defence techniques of the travellers.

More recently, Chinese immigrant workers introduced kung-fu to the United States in the 1840s. Over the following century, other martial arts reached the United States mainly due to the two world wars and subsequent wars on the Asian continent. Twentieth-century Europe also saw a rapid spread of the martial arts, as Asian masters travelled and shared their knowledge (Microsoft Encarta Online Encyclopedia, 2005). Some of the more prominent martial arts include judo, karate, TKD, kung-fu, thai boxing, kenpo, aikido and ju-jutsu. Martial arts have evolved from pure combat and self-defence systems into martial sports involving organized competitions. The Microsoft Encarta Online Encyclopedia (2005) list primary martial sports as karate, kickboxing, and the Olympic sports TKD and judo, and secondary martial sports as sumo wrestling and kendo.

Worldwide, more than 100 million people practise some form of martial arts (Microsoft Encarta Online Encyclopedia, 2005). Karate alone has thirty million practitioners worldwide (Matsuoka, 2005). Judo became an Olympic Sport in 1964 (IOC, 2005a) and TKD in 2000 (IOC, 2005b), whilst karate, sumo and wushu are all making serious attempts to join the Olympic movement and are currently on the list of recognised sports of the International Olympic Committee (IOC, 2005c). In 2004, karate was one of the sports shortlisted for inclusion in the 2008 Beijing Olympics, before it was decided not to introduce any new sports to these Games.
1.2 Taekwondo and karate as martial sports

The world governing bodies for TKD (World Taekwondo Federation - WTF) and karate (World Karate Federation - WKF) are both run under IOC recognised competition rules. In both sports, athletes score on their opponents by hitting them with either their hands or feet. The techniques employed are explosive and excellent examples of movements which require whole-body skill and coordination. A kick or a punch typically takes of the order of 100 to 600 ms depending on the technique and it is crucial for the athlete to be able to reproduce the required skills when under the pressure of short time-frames in competition. Due to the high risk of injuries, martial athletes cannot compete or even spar excessively and relatively safe training drills are devised to practice the competition skills. Hence, it is important to establish whether any differences between training 'maximum' and competition 'maximum' modes of execution for a movement combination may alter its effectiveness. This study investigates the kinematic and kinetic changes between these two modes of execution for a popular combination in TKD and karate. In order to fully appreciate the importance of effective skill reproduction in a short time-frame, a brief illustration of the rules for each sport will be given (for full rules and regulations, see: WTF, 2005; WKF, 2005). This illustration will highlight that even though both martial sports use techniques which are essentially the same; their goals are quite different, thus creating different control demands between both martial sports. Whereas in TKD the athlete aims to maximise the impact force on the target, in karate the athlete, at least when attacking the head, aims for exact control with little energy transfer to the target and focuses on proper retraction of the arm or leg.

1.2.1 Synopsis of rules for Olympic WTF taekwondo

In TKD, scoring techniques can result in one or two points. Athletes can also win a fight by knockout. An additional point can be added to the score if the opponent is knocked down by the scoring technique. This also implies that a technique, for which no score would have been awarded, can result in one point if it leads to a knock down. The WTF rules encourage powerful techniques (fig. 1.1) in order to gain the additional point. Elite fighters would therefore benefit from being able to deliver combinations with speed, accuracy and the power required to knock down their opponent. The scoring in TKD is continuous and the fight is not interrupted when a fighter lands a scoring technique.
1.2.2 Synopsis of rules for WKF karate

In karate, scoring techniques can result in one, two or three points. Illegal techniques can result in a penalty score with the opponent being awarded one, two or three points. To win, a fighter is required to build up an eight-point lead, or lead on points when the allotted match time is up. An illegal technique can also result in the immediate disqualification of the offending fighter. In contrast to TKD, scoring is intermittent, i.e. the referee will pause a match to award the score. Contact is controlled especially when attacking the face (fig. 1.2). Hence, athletes need to deliver techniques with speed and accuracy but limit the transfer of energy to the target. The higher scoring techniques require more skill to deliver accurately without excessive contact. Elite fighters typically attempt to gain a significant lead, or if behind to recover the difference, using techniques that score highly.
1.2.3 Implications of the rules for the study

It is clearly imperative for both elite TKD and karate athletes to be able to successfully reproduce high scoring combinations in the time-frames typical of competition. Often, athletes are able to perform the combinations very accurately if the time-frame is not restricted, however, in competition, athletes must seize opportunities and reproduce skills in time-frames that are often shorter than in training. As the time-frame is reduced, the reproduction of a skill may become more difficult and different motor solutions or strategies may be used to perform it. The athlete may change technique as body position, skill execution and contact force are compromised for speed of delivery. If this reduces the accuracy or the effective distance of a technique, the scoring potential may be adversely affected, the attack may result in a penalty or a miss leaving the athlete open to counter-attack.

1.3 Research Questions

It has been proposed that biomechanics research will shift from traditional motor learning to issues that are important for sport training (Zatsiorsky & Fortney, 1993). This study aims to combine biomechanical and motor control aspects of complex martial arts combinations used in high level competition to produce information of direct relevance to elite performers and their coaches. This consolidation of biomechanics and motor control has the potential to acts as a catalyst for skill enhancement in martial athletes (Brüggemann et al., 1999). In doing so, this research aims to identify the changes in execution and the potential weaknesses in the reproduction of a skill. Based on these findings, suggestions for the development of such skills will be made.

The main questions this study will address are:

Q1: 'Does skill execution by individual elite martial athletes differ when executed under competition maximum (100% mode) compared to training maximum (normal mode), and if so to what extent?'

Q2: 'What are the biomechanical causes for any observed differences between these modes and do they give an insight into the control of the movements?'
Q3: ‘Are the causes for any differences in execution the same in all individuals?’

Q4: ‘What recommendations can be made to martial athletes and their coaches based on the findings of this study?’

To address these research questions, 3D motion analyses of martial arts combinations were conducted for a number of elite performers (five from TKD and five from karate). Each subject was asked to perform a skill consisting of three techniques, chosen by coaches and typically used in competition under two different execution instructions; normal mode (training maximum) and 100% mode (competition maximum). Assessing the differences between these modes forms the basis of this study. A comparative approach is necessary due to the overabundant degrees of freedom (DoF) that exist during all movement (Bernstein, 1967): joints can move independently with one or more DoF; a number of muscles act on each joint; and each of these muscles consists of a high number of motor units. Subjects will demonstrate an inherent variability when executing the skill regardless of the mode of execution as described by Latash (1998):

‘[i]f the subject is asked to repeat the same movement several times, there will be a relatively high variability of the individual joint trajectories and a lower variability of the endpoint trajectory.’ (Latash, 1998, p.179)

In order to be able to make comparisons between both execution modes, the variability of each mode needs to be quantified. Skill, in terms of movement, usually refers to a person’s ‘learned ability to bring about a predetermined result with maximum certainty and minimum time and effort’ (Fitts & Posner, 1967). Oxendine (1984) defines motor skill as ‘a persistent change in movement-behaviour potentially as a result of practice or experience’. Similarly, Clark (1982) defines motor skill as ‘the harmonious coordination of component movement elements organized in time and space to achieve a desired goal’. Expanding beyond movement skill, a martial artist may evaluate sensory experiences related to the movement task to develop movement confidence. This entails ‘a cognitive evaluation of self in relation to task demands’ (Griffin & Keogh, 1982). This study illustrates that the concept of skill may not be as rigid as the above definitions suggest and that variability of movement may be part of skilful behaviour. The author previously investigated the relationship between skill complexity, accuracy and choice
reaction time in karate using a new choice reaction training device (Roosen et al., 1999). The findings of that study led to the interest in this research area.

1.4 Statement of purpose

The purpose of this study was to find biomechanical evidence for the motor control characteristics of complex skills performed with different modes of execution and identify what the potential causes of skill alteration or breakdown may be. To achieve this it was necessary to develop procedures to manipulate and process 3D movement data in a novel way to yield pertinent and accurate information.

1.5 Preliminary considerations and novelty

As noted earlier, 3D analyses of whole-body complex movements for the purpose of skill reproduction have yet to be attempted. Hence, a necessary preliminary stage to such an investigation is to ensure that the required research tools are available. For this study, the main source of information came from movement data captured using a VICON (Oxford Metrics Ltd.) motion capture system. Novel, but generic, protocols were applied to the data to yield pertinent information that is as accurate as possible. In particular, routines have been designed that allow the inclusion of functional methods for determining joint centre (JC) locations in the process workflow of analysing and modelling 3D motion data. The design of this workflow and the design of a whole-body model for accurate 3D analysis of whole-body movement represented intermediate goals required to allow the main research questions to be addressed.

An initial consideration was the processing methods for the 3D motion data. A preliminary investigation of existing models to produce kinematic and kinetic information from 3D marker data revealed that they did not possess the level of detail needed to describe the complex skills of this study. Hence, a model for accurate 3D analysis of whole-body movement needed to be created. A significant part of this process involved developing a method to include functionally determined JC in the process workflow of analysing and modelling the data, thus allowing all subsequent kinematic and kinetic calculations to be conducted within the motion capture software.

Only with these new procedures in place could data collection be initiated. The TKD athletes were the first participants in 2005. Data collection to estimate functional JCs using
a method, which at the time was considered amongst the most accurate (Gamage & Lasenby, 2002), was conducted immediately prior to that of the combination. The karate data collection took place in 2007 after substantial data processing for TKD had been completed. Some changes to the data capture protocol were implemented based on experiences with the TKD data processing. Also, during the course of the data processing, functional methods, which may be superior under certain conditions to that used in this study appeared in the literature (Camomilla et al., 2006; Ehrig et al., 2006). To determine the effect these methods may have had on the results of this study, additional stand-alone experiments using these methods were conducted towards the conclusion of this PhD. The experiments illustrated that although the new methods of approximating the JC may be more accurate in theoretical settings, this improved accuracy does not extend to \textit{in vivo} situations and further large errors are introduced by the method of JC location reconstruction during the athletic movement (Roosen et al., 2007).

1.6 Chapter Organisation

Chapter 2 presents a review of the relevant literature. The first section reviews a range of topics in movement studies namely:

1. Variability and control of movement, which includes theories on motor programs;
2. Initiation of movement and associated basic neuro-physiology;
3. Postural adjustments before the onset of movement;
4. Kicking;
5. Punching and striking;
6. Kinematic or kinetic chain and proximal-distal movement patterns; and
7. The importance of biomechanical feedback to athletes.

The second section reviews technical literature concerned with 3D movement analysis. It gives a brief summation of 3D movement reconstruction and marker tracking issues. As the inclusion of functional JCs was an important prerequisite to this study, a review of the JC estimation literature is presented.

Chapter 3 is the first of two method chapters. It describes the data collection workflow and generic procedures.

Chapter 4 is the second method chapter and explains the tools that were developed and used for this study. These include: the data capture procedure and data processing using a 3D motion capture system; the design of a 3D model to analyse whole-body
movement and the determination and implementation of functional JCs for athletic movement analysis; the method of determining target contact from marker kinematics and the processing of kinematic and kinetic output data; and the additional equipment such as the target pads, high speed camera and DV video.

Chapter 5 presents the TKD results which are divided into kinematic, target acquisition and kinetic results to investigate changes between execution modes and causes of movement variability.

Chapter 6 presents the karate results and is structured the same way as chapter 5 with additional results for the joint angle approximate entropy as a means to quantify movement variability.

Chapter 7 presents a discussion of the results. Firstly, a generic biomechanical discussion is presented. Secondly, the research questions are addressed. Thirdly, a general discussion follows, which elaborates on the study's findings in relation to motor control, and its limitations. This is followed by suggestions for future research based on experiences gained during this study. Lastly, the main conclusions of the study are presented.
Chapter 2

LITERATURE REVIEW

2.1 Chapter outline

This chapter comprises two sections. The first reviews research directly related to movement control and movement studies. The second reviews technical aspects associated with the data collection and processing methods required for this study.

2.2 Control and analysis of movement

TKD and karate combinations consist of complex fast targeted movements spanning multiple joints. Such movements involve a range of biomechanical and motor control issues. This study investigates movement variability and its causes during the performance of such combinations under different conditions in order to gain an insight into the motor control involved. In order to provide a proper background for this study it is necessary to gain an understanding of the underlying concepts involved in human athletic movement and motor control. The literature reviewed in this section will first give a theoretical background of movement production, motor control and movement variability. With this theoretical foundation in place, research areas of direct relevance to this study are reviewed. These areas are: movement initiation; postural adjustments related to movement; kicking and punching studies; proximal-distal studies; and biomechanical feedback studies.

2.2.1 Motor control and movement variability

Biomechanical analyses of martial arts combinations can be used to estimate kinematic and kinetic information. Any observed differences in the execution of these combinations may be caused by variability in neural control and mechanical work. Therefore, it is necessary to consider some of the underlying theories of motor control relevant to movement in martial arts techniques, before engaging in a biomechanical analysis.
2.2.2 Motor programming aspects

In the past, the control of slow human movement has been described using closed-loop theories. The premotor cortex, which coordinates skilled movement (Creager, 1992; Latash, 1998), together with motor association areas of the brain form the executive block involved in movement codification. This executive block is connected to the thalamus and the basal nuclei, which provide sensory input used by the executive to select a set of instructions to best meet task requirements and produce an appropriate output. These instructions are relayed via the thalamus to the motor cortex which initiates patterns of action potentials, some of which are transmitted by motor axons directly to motor units which produce movement. Collaterals of these axons return signals to the cerebellum and the basal nuclei, to continuously provide feedback information on body position and movements allowing the instructions to be constantly revised (Creager, 1992; Latash, 1998).

However, the durations of fast human movements are too short for feedback to take place. The concept of a prestructured set of central commands for such movements, which was first proposed by James (1890) and more recently has been called a motor program (Keele, 1968), is based on open-loop control (Schmidt, 1991, Ch.4; Schmidt & Lee, 1999, Ch.6), and was further developed into a generalized motor program (GMP) by Schmidt (1988). In open-loop control (fig. 2.1) the output cannot be altered through feedback but only by alteration of the program. Wickens et al. (1994) suggested a theory of cortical cell assemblies as a possible neural mechanism for motor programming, stored in a form of strengthened synaptic connections between cortical pyramidal neurones that determine which combinations of corticospinal neurones are activated when the cell assembly is ignited.

A GMP contains information about the order and temporal structure of events and the relative force with which to produce these events. It can be applied to different types of movements, or motor classes, and can be parameterised in order to affect overall movement amplitude, overall movement duration and limb selection. Movement governed by a GMP is a consequence of a number of sequenced muscle contractions causing mechanical impulses. A GMP demonstrates time- and force rescalability, which are considered its invariant features. Time rescalability implies that movements with different durations demonstrate the same phasing of contractions (Schmidt & Lee, 1999). Force rescalability generally means that to move twice the distance in the same time, the velocity at each stage of the movement must double. Thus, the impulse is doubled as well by
doubling the amplitude of the force-time impulse at each instant. Similarly, if the movement distance remains the same, but the movement time is halved, the average velocity at all instances of the movement must double. Hence, the amplitude of the force-time function increases by a factor of four (Zelaznik, 1993; Schmidt & Lee, 1999). Time rescalability of the GMP led to impulse-variability theories being used to explain the linear speed-accuracy trade-off (SATO) observed in most fast movements (Schmidt & Lee, 1999) (§2.2.4). These theories also explain the force rescalability of the GMP (Schmidt et al., 1979; Meyer et al., 1982) and incorporate force production variability principles.

Force production variability has been found to be linearly related to force production for moderate force levels up to 65% of a subject’s maximum (Schmidt et al., 1979; Sherwood & Schmidt, 1980; Newell & Carlton, 1985; Schmidt & Lee, 1999). However, for force levels of over 65% of maximum, variability in force production has been shown to decrease (Sherwood & Schmidt, 1980; Ulrich & Wing, 1991; Carlton & Newell, 1993; Schmidt & Lee, 1999) or at least increase at a lesser rate than at lower force levels (Newell & Carlton, 1985; Sherwood, Schmidt & Walter, 1988; Ulrich & Wing, 1991; Carlton & Newell, 1993). This suggests that, in contrast to the linear SATO (§2.2.4), spatial accuracy may increase due to increased consistency in force production and therefore increased consistency of the limbs’ positions throughout an action.

If motor programs are used for the control of the TKD and karate combinations, it is likely that more than one is used for a skill of this duration (about one second) (Schmidt & Lee, 1999). Each of these motor programs that produce a skill can be thought of as a unit.
of action (Schmidt & Lee, 1999) which is characterised as a sequence of behaviour that demonstrates invariance in timing of certain temporal events, or landmarks. When this invariance disappears, this indicates the end of one unit or a boundary between the former and the next unit (Schmidt & Lee, 1999). Units of action have been identified by highly correlated kinematic landmarks on position-, velocity- and acceleration-time histories of coincident-timing task trials (Schneider & Schmidt, 1995).

The GMP uses schemata for motor learning (Schmidt, 1975). Schemata are sets of rules acquired through repeated practice that define the relationship between the required parameters and the outcome of a task (Shapiro & Schmidt, 1982; Schmidt, 1991, pp.209-210) (fig. 2.2). For fast movements recall schemata are used; after identification of the desired task outcome, a suitable motor program is selected and parameterised using information held in the schema (Shapiro & Schmidt, 1982; Schmidt & Lee, 1999, pp.371-374).

![Figure 2.2: Recall schema. A hypothetical relationship (grey line) between movement outcomes and parameters that were used to produce them, where the data points (*) indicate the individual movements obtained through repeated practice (adapted from Schmidt & Lee, 1999)](image)

Newell and Barclay (1982) state that schemata in cognitive psychology literature and in motor skills literature have slightly different connotations. The differences consist of how the 'nature of knowledge of action' is represented and what variables can be applied. In the cognitive approach it is the act itself that is put forward by the schema, whereas in the motor control approach it is the details of the response that are specified. The debate is really about what intelligence is attributed to the schema and to what extent it codifies the desired action. If purely considering the power of the schema, the argument would appear to be a philosophical one, as no one can ascertain, as of yet, the exact processes in
movement codification. Newell and Barclay (1982) state that although these interpretations are very different, they are not mutually exclusive and that there is a need to find a link between the two. They argue that schemata are prototypes allowing for 'response generalization', and that it should become apparent whether it is the act itself, or the details of response specifications, that are the variables of the schema. The cognitive approach stipulates that if there is a schema for punching, than the act of punching should transfer well to all movements involving a punch. According to the motor control approach it is the parameters of the schema for punching that should transfer well across different punches. It may be incorrect to follow the cognitive approach as executing a punch in one situation does not transfer to doing it in another as the conditions have changed. Executing martial arts techniques on their own is very different from executing them as part of a combination. On a purely mechanical level, many additional forces and torques come into play. On a muscular level, muscle properties have changed as muscles are at different lengths and are contracting with different velocities. Furthermore, the history-dependent characteristics of a muscle will affect its force production. It appears more likely that a different motor program is used in each case, and hence the motor control use of schemata seems more appropriate.

The computation of a response using recall schemata, still requires a set amount of time which implies a cognitive involvement. The task result needs to be established and appropriate parameters need to be chosen. Martial athletes are, however, able to produce actions in such times that do not allow any computation and therefore may pre-program the movement, i.e. the desired motor program has already been selected and parameterised before the stimulus to which to react is presented.

The movements of the arms in punches and the legs in kicks have been categorised as ballistic movements and are pre-programmed (Zehr et al., 1997). In a compound martial arts combination additional movements are included however, suggesting that only certain components of a combination may actually be ballistic. For example, when a martial athlete lunges forward with a punching combination, the arm movements during the punch may be ballistic but the actions of other segments involved in the movement are almost certainly not. The movement of these non-ballistic segments can therefore be altered which may in turn alter the trajectory of the punches. The ballistic movement in a combination may not be initiated until certain other component movements of a combination which allow alteration based on peripheral feedback have been completed satisfactorily. Furthermore, a martial athlete who has started an attacking combination as
the opponent moves off to the side can successfully correct the trajectory of the attack even though the punching and kicking techniques are indeed ballistic. Schmidt and Lee (1999) suggested viewing this ‘blending of open- and closed-loop functioning’ by considering a hierarchical control in which the open-loop structure sits on top of a closed-loop process which ensures the movement’s intended goal is reached regardless of such changes.

Zehr et al. (1997) suggested that once the command for a ‘true’ ballistic movement has been centrally formulated and sent to the motoneurons, their activation can no longer be modified based on peripheral feedback. A similar yet more adequate account by McGarry and Franks (2003) suggested that a voluntary movement reaches a point in its process where it turns from a voluntary, controlled process into an involuntary, ballistic process. This point is called the ‘point of no return’. However, in this interpretation it is the ballistic component of a processing stream, not the whole movement, which cannot be inhibited once it has been entered and the onset of further action cannot occur until this process is completed (McGarry & Franks, 2003). Hence, there is a time limit for the motor system to alter or stop an action based on new peripheral information (Schmidt & Lee, 1999, Ch.6). This point has been shown to occur before movement onset (Henry & Harrison, 1961).

Figure 2.3: Tri-phasic EMG pattern. For a fast elbow extension, the first agonist burst from the triceps accelerates the arm as indicated by the increase in angle. This followed by an antagonist burst by the biceps, which keeps the arm moving at a constant velocity and then decelerates it. The second agonist burst counters the antagonist burst and brings the movement to a halt (adapted from Latash, 1998).
Ballistic actions may be initiated differently by the brain and are associated with a high frequency discharge of the motoneurons, they may involve preferential use of fast twitch motor units and often exhibit agonist-antagonist coactivation or a tri-phasic activation (fig. 2.3) pattern, and if commenced against a background of tonic activity, there may be agonist pre-movement depression or pre-movement silence (Zehr et al., 1997).

Movements are accelerated and decelerated by two agonist-antagonist burst pairs: the acceleration is controlled by an agonist burst before movement onset shortly followed by an antagonist burst, and the deceleration is controlled by an antagonist burst followed by an agonist burst; a constant velocity phase with tonic activity can be observed between both burst pairs for prolonged movements although for shorter movements a tri-phasic pattern may arise from the merging of the two burst pairs resulting in a smooth transition from acceleration to deceleration (Cooke & Browne, 1990).

It has been suggested that in high speed ballistic movements, such as punches and kicks, a positive relationship exists between the extent of pre-movement depression of tonic activity and subsequent phasic innervation: a maximal number of motor units (fig. 2.4) has to be recruited, and if these units are already tonically active, they must be released from tonic activity for optimal synchrony (Conrad et al., 1983). In other words, pre-movement silence allows all available motoneurones to fire at the same time, thus creating a stronger contraction. The acceleration and deceleration of a ballistic movement can be controlled independently to produce movements with different temporal characteristics (Cooke & Browne, 1990).

![Figure 2.4: Innervation of motor units. A motor nerve consisting of three motor neurones relays signals between the spinal cord and three motor units of the biceps muscle in the upper arm (adapted from www.cptc.ctc.edu/library, 2007)](image-url)
Another example of a martial arts technique being altered almost instantly would be when a fighter needing to exhibit touch control when punching an opponent's head makes almost instantaneous adjustments to the punch on contact if the opponent did not move as far back as initially expected. In other words, a certain feedforward mechanism has prompted a change to the punch based on mechanical peripheral feedback, or a preflex, which does not involve re-computation. A preflex has been defined as 'the zero-delay, intrinsic response of a neuromusculo-skeletal system to a perturbation' (Brown & Loeb, 2000) and presents itself as a high frequency interaction between the neuromusculoskeletal system and the mechanical work environment (Campbell & Kirkpatrick, 2001). Preflexes limit the initial reaction of the neuromusculoskeletal system (Grillner, 1972) and reduce potential instability from high neural reflex gains and neural transmission delays (Hogan, 1990). Muscles immediately alter their actions based on the preflex, as there are no delays associated with sense-command loops (Cham et al., 2000). It is possible that a similar mechanism is used when a martial athlete is required to alter a technique's execution as described in the above scenario.

Further support for the motor system being able to quite readily produce alternative trajectories in an attempt to achieve the original goals comes from triggered reaction experiments to perturbations (Schmidt & Lee, 1999). Triggered reactions have a loop time of between 80 to 120 ms which is longer than long-loop reflexes but shorter than normal reaction time responses, perhaps because they bypass some stages of information processing and no response selection is used (Schmidt & Lee, 1999).

Variability in movement can be explained by errors. Two main categories of errors can lead to an incorrect movement outcome: errors in program selection and errors in program execution. The former can be due to choosing the wrong movement pattern, e.g. moving in the wrong direction, or applying the incorrect spatial-temporal pattern, e.g. a kick could be placed too high or thrown too late. Errors in program execution occur due to unexpected disruptions whilst the program is running, e.g. a sudden loss of balance when executing a kick (Schmidt & Lee, 1999, Ch.6).

A modern viewpoint of the motor program by Schmidt and Lee (1999) reflects the above considerations on corrections of fast movements. Although the motor program is essentially an open loop concept, certain aspects in keeping with feedback processes have been incorporated. The program is an abstract representation of an action which produces a movement without regard to sensory information, making errors in program selection possible. Once initiated, a pattern of action is carried out for at least one reaction time
even though environmental information may indicate an error in program selection. During the program's execution, however, corrections for minor errors can be implemented to ensure the movement is carried out faithfully.

All voluntary movements exhibit natural variability due to the number of DoF for any limb (Bernstein, 1967). It is impossible for the executive of the central nervous system to compute all of these possibilities as this would take an enormous amount of time and storage. Hence, the executive is only responsible for the selection of the motor program, which in turn controls the degrees of freedom as it is executed (Latash, 1998, Ch.21; Schmidt & Lee, 1999, pp.142-143). Similarly, Shapiro and Schmidt (1982) state that:

'the executive selects the co-ordinative structures, orders up the units one after another, and modulates the units temporally. Details of the movement requirements are relegated to lower levels of control. The response programming mechanism then, is one of multiple levels of computing, in which each successive computation brings the movement response closer and closer to an approximation of the environmentally determined response'.

This notion led to the equilibrium point theories (Feldman, 1966a; Feldman, 1966b; Polit & Bizzi, 1978; Pöllit & Bizzi, 1979; Feldman, 1986), which postulate that only the movement endpoint is programmed, and that muscle properties determine the trajectories (Schmidt & Lee, 1999, p.191). According to these theories the central nervous system can move an image of a working point along a desired virtual trajectory which is always ahead of the actual working point, and it is this position difference that determines the forces in agonist and antagonist muscles (Latash, 1998). Hence, there are no computational problems as muscle forces are not calculated by the central nervous system, but appear due to a shift of the central image of the working point. Although these theories have provided close agreement for simple movements about a single joint, they struggle to explain complex movements (Schmidt & Lee, 1999).

Although the rigidity of the GMP is appealing and allows for relatively simple explanations of movement success and failure, it does not fully account for observations made in complex whole-body movements and combinations, such as those typically performed in martial arts. The limitations of these theories are that they are based on experiments using simple non-sporting movements and their findings are then used to explain all human movement including sporting actions. Although some concessions have
been made to the earlier notion of the GMP, which allow lower level feedback to influence fast movements, spontaneous movement invention and variability in movements which still achieve the original goal are not easily explained. For less skilled performers the rigid notion of the GMP for movement reproduction may be sufficient, however, for more skilled performers this is not necessarily so. The GMP explains the faithful reproduction of skills at different speeds. Yet, athletes demonstrate more freedom in execution when performing such combinations which cannot be explained by different parameterisation alone. The assembly of a series of movements and their interactions within the motor system may result in the successful completion of the combination even though so-called errors may have occurred during its execution.

2.2.3 Dynamical systems

In contrast to motor programming theories, which employ complex equations where a certain input must yield a certain output and which explain any deviations through errors, dynamical systems theory for motor control uses rather simple equations and interactions where a given input can yield a range of valid complex outputs. Variability is not interpreted as a problem but, within certain limitations, as a positive factor in a range of issues for system control. Hence variability is seen as an index of movement fluctuation rather than an indication of movement error (Newell & Corcos, 1993).

This approach disputes that a plan created by the command centre can account for all the variations in skilled movement and suggests that

‘movements emerge or self-organise from a dynamical interaction of numerous variables in the body, the environment and the task. These variables impose constantly changing constraints upon movement and the movement pattern that emerges is a function of these constraints’ (O’Dwyer, 2005).

In dynamical systems theory, the number of biomechanical DoF of the motor system is reduced through the development of coordinative structures and Bernstein’s problem can be expressed as:

‘Each and every movement comprises a state space of many dimensions; the problem of coordination, therefore, is that of compressing such high-
dimensional state spaces into state spaces of very few dimensions.' (Turvey, 1990)

The reduction in complexity encourages the formation of attractor states for goal directed actions. These states are characterised by a highly ordered and stable system, which results in consistent movement patterns. Variation between attractor regions allows for flexible and adaptive motor behaviour (Glazier et al., 2003). Skilled athletes can demonstrate both of these characteristics.

Kelso and Ding (1993) argued that variability should not be viewed as error but as an ‘essential feature of motor behaviour’. If the task conditions remain constant the trajectories of a multi-DoF system are very similar and can therefore be conceived as attractors. However, as there are a number of spontaneous and variable results for a given motor task, there must be an infinite number of trajectories.

Another factor that may affect movement variability is history dependent muscle properties. It has been shown that isometric force following muscle shortening is depressed for a long time, whilst following muscle lengthening isometric force is enhanced (Wu & Herzog, 1999; Witvrouw et al., 2004). These length change effects will affect the force output of a muscle if it contracts shortly after. The altered force production could lead to altered positions of body parts.

In contrast to motor learning which has traditionally been viewed as reducing variability in performance, the acquisition of coordination can be regarded as the search for optimal movement strategies. Variability in component movements within so-called ‘search processes’ for attractor states would be essential to the development of new coordination and adaptive systems and may lead to a reduction in performance variability and to task-specific coordinative structures by steadily releasing frozen degrees of freedom (Vereijken et al., 1992). Variability provides task-relevant information and therefore is an ‘essential feature of adaptive control rather than irrelevant activity or noise’ (Riccio, 1993). Optimal trajectories in targeted movements minimizing post-movement variance based on signal dependent noise can be learned by repeating the same movements with different velocities (Harris & Wolpert, 1998). Thus, variability during learning of a new martial arts skill may indeed be positive and information gained from this variability may lead to a more robust performance of the skill.

Like the GMP, dynamical systems theory for motor control has very appealing aspects. Almost instantaneous alterations to perturbations can be explained more easily
through interactions, although it is not always clear how the motor system achieves this. Variability in movement production is seen as a positive quality allowing for the synthesis of motor solutions based on interactions throughout a movement. As outlined in §2.2.2, the GMP struggles to explain alterations to executions without considering lower level feedback, and views variability in movement as errors. Freezing DoF in early learning to reduce variability in dynamical systems theory is not dissimilar to the notion of the GMP. Similarly, an attractor state for a movement may be compared to a GMP for that movement. Variability in technique execution by elite athletes to achieve its goal in itself may be a manifestation of skilful behaviour, implying that without this variability the goal may not have been achieved. Hence, some notions of dynamical systems theory may be more suited to explaining certain parts of complex movement reproduction, although they cannot do this without the basis of an initial frozen attractor state, or GMP.

2.2.4 Speed-accuracy trade-offs

As mentioned earlier, the time rescalability of the GMP explains the linear SATO in fast aimed movements as feedback may not be possible (Schmidt & Lee, 1999). However, some research has shown that this time rescalability is not necessarily a condition of a linear SATO (Gielen et al., 1985; Zelaznik et al., 1986). In brief the linear SATO postulates that for a fast aimed movement spatial accuracy decreases for larger movement amplitudes and shorter movement times, and temporal accuracy increases for shorter movement times. At force levels under 65% maximum (§2.2.2) the impulse-variability theories reproduce the linear SATO. However, since force variability lies at the foundation of impulse-variability theories (§2.2.2) they also indirectly describe that spatial accuracy may increase at near maximal force levels.

Early research by Fitts (1954) where feedback was utilised suggested that the SATO showed a logarithmic relationship between minimum movement time and the ratio of movement distance to the target width. Many different mathematical formulations and applications have been assigned to Fitts' Law (Plamondon & Alimi, 1997). Most experiments examining the linear SATO show some typical characteristics. The displacement data is a smooth ogival curve; the velocity profile is bell-shaped with a single peak; and the acceleration curve displays two components with positive acceleration until maximum velocity is reached and negative acceleration thereafter (Zelaznik, 1993). The presence of signal dependent noise in the neural signal to the muscles has been suggested as a control mechanism as it reproduces these characteristics by placing a lower limit on
the final positional variance given by the minimum-variance trajectory (Harris & Wolpert, 1998). As karate requires touch control when attacking the head, one might expect these linear SATO characteristics to be observed.

The acceleration profiles are clearly important in defining joint moments and muscle forces. Zelaznik et al. (1986) showed that for non-zero end velocities, this parameter was linearly related to average movement velocity, suggesting that the asymmetry between positive and negative acceleration grows as average velocity increases. Schmidt et al. (1979) found that when the subject was required to pass the target in a rapid-timing task, i.e. there was only positive acceleration, the effective target width at the end of movement time was independent of movement time but linearly related to distance. These studies do not support the symmetric impulse-variability model (Zelaznik, 1993) but are relevant to this investigation since kicks and punches may have a non-zero contact velocity. In TKD and in karate when attacking the body at least, techniques can go ‘through’ the target and hence will show little or no deceleration. Generally, SATOs in rapid human movements ‘are far from being completely understood’ (Plamondon & Alimi, 1997).

In order to hit a target with their foot or fist, martial athletes need to resolve a number of issues. As the target will be moving during the execution of the combination, they will have to demonstrate some degree of timing accuracy (Schmidt & Lee, 1999). Timing accuracy is generally measured by checking whether a subject is able to touch an approaching target. The target is moved at a range of velocities, so a relationship can be determined between the accuracy and the target velocity. With a higher approach velocity of the target the movement time is reduced and hence less timing errors should occur. Second, they must get a good hit with the target and therefore must also demonstrate spatial accuracy (Schmidt & Lee, 1999). Third, the delivery of the technique must be done with the correct amount of force. All three of these control issues have been studied extensively for relatively simple movements (Schmidt et al., 1979; Meyer et al., 1982; Carlton & Newell, 1993; Newell & Corcos, 1993; Zelaznik, 1993; Schmidt & Lee, 1999) but not using complex multi-joint whole-body movement.

Speed and accuracy are clearly important in martial arts. Although the relationship of these aspects has been explored using a range of paradigms, the set-up was always restricted to simple movements and sub-maximal speeds. The literature does not account for experiments where whole-body movement is required nor does it include studies where more than one aimed movement needs to be executed. In this study the accuracy, speed
and impact force of multiple complex aimed movements, and the effect of different modes of execution on these parameters, are investigated.

2.2.5 Initiation of movement

A comprehensive background to the mechanics of hitting and kicking was given by Elliott (2000). Although Elliott did present some examples from martial arts and boxing studies, the majority of the information came from other sports. The account describes the preparation, backward and forward swing of the kicking or hitting limbs, and impact and follow-through phases of the movement. In this section only the preparation phase will be considered. Subsequent sections will elaborate on the other phases.

Elliott (2000) stated that prior to moving off the spot an athlete unweighs by flexing the knees causing the body to accelerate towards the ground. Such a counter movement produces a stretch shorten cycle (SSC), which has been shown to increase the velocity of the subsequent movement (Bobbert et al., 1986; Takarada et al., 1997; van Ingen-Schenau et al., 1997). The mechanisms believed to be responsible for this increased velocity are disputed (van Ingen-Schenau et al., 1997) and include increased time for force development, stored elastic energy, reflexes and conformational changes (Jessop & Pain, 2004). Some researchers have shown that when the knee flexion ceases due to the eccentric contraction of the quadriceps muscles, the tension created in these muscles results in the storing of elastic energy (Witvrouw et al., 2004) and that this may assist in the subsequent concentric action if the leg is extended about the knee (van Ingen-Schenau et al., 1997; Elliott, 2000). There has been much debate on the effect of this stored elastic energy re-utilisation in SSCs (van Ingen-Schenau et al., 1997; Witvrouw et al., 2004). It has been shown that the need to store and utilise elastic energy varies from sport to sport (Witvrouw et al., 2004). Sports requiring rapid development of isometric or concentric force may benefit from a stiffer muscle-tendon unit, whereas sports requiring a high amount of positive work-loops may benefit from a more compliant muscle-tendon unit in order to save metabolic energy (Witvrouw et al., 2004). Martial arts techniques require both of these aspects in different muscle groups but often also in the same muscle groups. Elite karate and TKD athletes typically maintain a light bounce on the balls of their feet, i.e. a cyclical work-loop, in order to be able to initiate explosive movements and remain mobile throughout the fight. However, in other muscles, a stiffer muscle-tendon unit produces a more powerful hit due to the rapid force development if movement time is limited. The martial arts techniques in this study are mostly explosive, involving a number
of maximal SSCs. Some studies have shown that elastic energy does not explain work enhancements in discrete explosive movements and there is no substantial conclusive evidence to support or reject that elastic energy enhances mechanical efficiency in cyclical work-loops and whether the SSC in fact enhances muscle efficiency (van Ingen-Schenau et al., 1997). However, the research community is divided on both subjects. Nonetheless, elite martial athletes require muscle-tendon units which can produce explosive movements, i.e. lunge into an attack, and efficient work-loops, i.e. bouncing for the duration of a match.

To impact a target correctly, a martial athlete needs to move rapidly and be balanced at the moment of impact. When static, one is most stable if the gravity line is central to the base of support (Elliott, 2000). However, athletes need to position their centre of gravity near the edge of the support base in the direction in which movement is to take place. If this direction is uncertain, the athlete tends to move the body weight onto the toes, making it possible to move quickly in any direction (Elliott, 2000). During movement, however, one needs to maintain dynamic balance as other accelerations are present allowing the centre of gravity to move away from the centre of the base of support. In fact, for certain actions which produce high accelerations, such as a kick, it is perfectly possible to be off balance, and be falling whilst kicking, as long as the leg is retracted in time (§2.2.6).

When presented with a sensory-perceptual issue, an athlete will make extensive use of cuing when producing a motor response (Elliott, 2000). If a martial athlete is presented with a warning signal before the opponent’s movement he or she will react to this signal rather than to the actual movement without cues or with later cues. Therefore, it would seem they react faster. This is not entirely correct as the reaction time is likely to remain the same but the fore-period has changed. The time between the intended go signal after the used cue and the initiation of a reaction has thus decreased due to anticipation (Keele, 1973; Schmidt, 1991) resulting in an apparent shorter reaction time. The cues may include a change in the position of opponent’s head, hands, feet etc. as well as concerting movements of these body parts and changes in the opponent’s gaze direction (Mori et al., 2002) (fig. 2.5). The athlete must decide whether or not to initiate a technique and if so, when and with what timing. Elliott (2000) suggested that this requires selective attention and that more experienced athletes are ‘able to process critical information earlier in the opponent’s action’. Additionally, experienced athletes are faster than novices at ‘responding and accurately predicting’ the path of the target. Although the study Elliott referred to is based on hitting a baseball, a similar argument is likely for martial artists kicking or punching a target.
Indeed, Mori et al. (2002) found that elite martial athletes had better choice reaction times than novices in karate specific tests and deduced that this was due to a superior ability to anticipate the opponent’s attack. The athletes had better decision making skills, better ability to extract critical information from the opponent’s movements, and required less visual information to initiate an appropriate response to an attack. No significant difference in non-karate specific simple visual reaction time tests was observed.

The literature on movement initiation is again limited to single techniques. Hence, no comments can be made on the issues reviewed above such as balance, decision making and reaction times for multiple techniques. In progressive martial arts combinations, skills may need to be adjusted as the combinations unfold. Movement variability (§2.2.2 and §2.2.3) may give an indication where in the body these adjustments are initiated and how the martial athlete controls them. Furthermore, the study should provide information on whether these adjustments become more pronounced when the execution modes of the combinations are changed.

2.2.6 Postural studies

Martial arts techniques can be described as fast voluntary movements. Latash (1998) described two sources of postural perturbations that are associated with such movements. Firstly, the projection of the centre of mass is altered by a change in body geometry. The centre of mass may move outside of the support area and therefore must be corrected. Secondly, during arm and leg movements, torques are changed at a number of joints, including those involved in postural control. As a result, fast voluntary movements are
almost always associated with changes in activity of postural muscles. Changes in activity that occur before the onset of the voluntary movement are called ‘anticipatory postural adjustments’ whereas reactions to voluntary movement and signals from proprioception are called ‘compensatory reactions’ (Latash, 1998). Martial arts movements involve both types of adjustments. This section discusses postural pre-requisites to voluntary movement and strategies of maintaining balance whilst moving as related to both arm movements and leg raises or kicks.

Bouisset and Zattara (1981) investigated postural movements that occurred in the lower limbs and pelvis before a voluntary movement of the upper limb. They deduced that ‘the preparation of movement serves to create [...] a movement whose forces of inertia would [...] balance the inertia forces due to the movement of the mobile segment which tend to disequilibrate the rest of the body’. This provided compelling evidence for the theory that anticipatory movements were directly opposed to the forthcoming voluntary movement and were specific to the voluntary movement suggesting that they were pre-programmed.

In a later study, Bouisset and Zattara (1987) investigated rapid arm flexions bilaterally, unloaded unilaterally and unilaterally with an added load. Although the time durations and amplitudes of the anticipatory movements differed depending on the task, it was found that for given experimental conditions, the amplitude or the time of each biomechanical variable was reproducible both intra-individually and inter-individually. Whole-body kinetics started before and ended after the kinetics of the upper limb. The duration of the anticipatory response was found to be related to the duration of the upper limb movement and the anticipatory component of movement corresponded to an important fraction of the peak resultant force for the movement. The duration of the anticipatory movement was found to increase with the ‘dynamic asymmetry’ of the impending movement. Furthermore, their results suggested that voluntary movement and the concomitant anticipatory movement were part of the same motor program, and again it was concluded that anticipatory movements created forces that will balance out the forces created by the intended voluntary movement.

The same study also investigated consecutive postural adjustments (compensatory reactions). In contrast to anticipatory movement, time increased from unilateral to bilateral movement. The duration of the consecutive adaptation was also related to that for the voluntary movement. The relationship was different to that for anticipatory movement.
Cordo and Nasher (1982) also investigated postural adjustments associated with rapid arm movements and found that anticipatory postural activities occurred together with segmental stretch reflexes and self-initiated movements. These anticipatory movements were generally faster than voluntary adjustments to balance. Temporally organized linkages between leg and arm activation were mediated to some extent by fast pathways organized at a low hierarchical level. An important conclusion of this study was that voluntary postural adjustments 'share[d] many temporal and structural properties with automatic postural adjustments elicited by support-surface movements'. Both were very specific in locus and magnitude to the quality of postural equilibrium suggesting that neural pathways for voluntary movement may be inhibited until the effects of postural adjustments can counterbalance the voluntary movement.

In kicking, postural adjustments are even more crucial. Mouchnino et al.'s (1992) compared experienced dancers and naïve subjects during unilateral leg swings. The transfer of body weight to the supporting leg was divided into two components: the 'ballistic' component, which was initiated by a thrust exerted by the kicking leg; and the 'adjustment' component, in which the centre of gravity settled into a new steady state. Achieving the new position for the centre of gravity was a pre-requisite to the leg swing. Dancers completed the weight transfer before commencing the movement, whereas naïve subjects had not yet finished the transfer. An important factor to consider here is that these subjects were not constricted by time. If having to execute a kick to hit a target which will only be available for a brief period, transferring the weight first may be too costly even though one is kicking on the spot. As the target is likely to be moving away, it would appear sensible to execute the kick accompanied by a ballistic phase initiated from the support leg in the direction of the target. Hence, the observations by Mouchnino et al. (1992) related to weight transfer are unlikely to apply to this study.

As indicated earlier, when kicking in a fight, one must maintain dynamic balance which means that movement accelerations allow the centre of gravity to move away from the supporting leg unlike Mouchnino et al.'s (1992) suggestion that it is essential to displace the centre of gravity towards the supporting leg in order to kick. Two different control strategies were employed in their study: dancers used a 'translation' strategy which ensured the verticality of the head-trunk axis; naïve subjects used an 'inclination' strategy, using external rotation of the supporting leg accompanied by a counter-rotation at neck level to ensure the eye line remained horizontal. Dancers showed reduced oscillations of the centre of gravity compared to the naïve subjects. Control strategies when kicking in
martial arts combinations are likely to differ to those observed here, as kicks, not leg
swings, are executed with larger accelerations and aimed higher, and the upper body must
be kept in a position where it is not open to counter, easy to regain a guard position, or
continue the attack. Mouchnino et al. (1992) also suggested that the head and trunk
orientations must be maintained whilst kicking as they are used for reference in the
organization of movement and form the egocentric reference frame used to calculate
movement trajectories. If kept vertical this frame coincides with the gravity axis therefore
simplifying the calculation of gravitational forces and trajectories. Yet, fighters bob and
weave, producing several combinations including kicks effectively, whilst moving rapidly
and maintaining a guard position; during all of which the egocentric reference frame may
not be vertical. Athletes from many other sports, including gymnastics and ice skating,
also perform skills with twisting and spinning where the egocentric reference frame is not
in a vertical position.

Similar results to Mouchnino et al. (1992) were obtained by Reifel Saltzberg et al.
(2001) for changes in body position of non-martial artists whilst learning a whole-body
kicking movement. Initially, movements of the arms and legs counterbalanced each other.
As learning progressed, subjects adapted the orientation of the trunk which may have
prevented the counter rotation of the arms and legs displayed in early learning therefore
allowing more backward lean. They also displayed ‘an initial posture which corresponded
to the amount of counter-twist associated with foot lift-off’.

Postural adjustments are likely to be affected by the amount of force that is to be used
when executing techniques. As explained in the revision of the rules of both sports, TKD
allows full contact techniques (§1.2.1), whereas karate demands touch-control when
attacking the head (§1.2.2). Béraud and Gahéry (1995) investigated this during the
execution of a low kick in French boxing (savate), and, as for previous studies, discovered
that motor events started before the onset of voluntary movement. For strike mode, early
postural adjustment was longer in duration and larger in magnitude since greater forces are
required in the kick, thus larger adjustments to counter their effects are needed which take
more time to produce. In touch mode, the time of the voluntary movement was
significantly longer, but could be initiated earlier since the duration of postural adjustments
was less. The new position for the centre of gravity must also cope with the effects of the
forces generated by the voluntary movement. This study, although based on more dynamic
movements than previous studies, still involved just one kick of the back leg without
advancement towards the target. Subjects started from within range and the target
remained stationary. If a kick is thrown as part of an attacking combination postural adjustments may be different.

Similar to the initiation of movement, studies into postural adjustments have been limited to single techniques. Additionally, when such studies required a target to be hit or kicked, they were done from within range, e.g. subjects were not required to move their bodies towards the target whilst kicking. Most studies relating to the investigation of technique have compared experts with novices or monitored the learning processes of novices. In one case, different modes of execution were considered but these related to impact conditions only. Data from this study will offer information on postural changes related to multiple techniques and how these adjustments are affected by different execution modes.

2.2.7 Kicking studies

The literature accounts for a wide array of research into the biomechanics of kicking (Roberts et al., 1974; Huang et al., 1982; Asami & Nolte, 1983; Putnam, 1983, 1991, 1993; Phillips, 1985; Levanon & Dapena, 1998; Elliott, 2000; Nunome et al., 2002). Usually, the studies relate to ball kicking and research into kicking in martial arts is less prominent (Feld et al., 1979; Béraud & Gahéry, 1995; Sørensen et al., 1996; Hong et al., 2000; Reifel Saltzberg et al., 2001; Sforza et al., 2002; Robertson et al., 2004). This section first describes the phases observed during kicking before discussing studies which looked at the variability in kicking. Examples are provided of kicking velocities and execution times both from martial arts and other sports.

As illustrated in the section on postural adjustments (§2.2.6.), kicking is a non-planar movement during which the trunk and lower limbs usually rotate in such a manner to 'appropriately position the body for the forward swing' (Elliott, 2000). Kicking (and hitting) movements typically display a SSC, which athletes can use to aid performance (Bobbert et al., 1986; Takarada et al., 1997; Elliott, 2000). However, this ‘wind-up’ may not be the best strategy in some techniques for competition karate, where the time from movement onset to completion is more important than impact force and, to a certain degree, maximum speed. A long wind-up would present an obvious visual cue to the opponent (Mori et al., 2002) who could score with a faster technique. In contrast, in TKD the wind-up strategy may be quite useful as knockdowns are allowed and fighting is continuous. Landing a more powerful technique despite its longer movement time may
outweigh the disadvantage of presenting visual cues, as a counter of shorter movement
time is likely to result in a less powerful technique (fig. 2.6).

Figure 2.6: A powerful body kick. The TKD athlete on the right connects with the target as the opponent’s kick misses (www.sporttaekwondo.uk.staffs.org, 2005)

Phillips (1985) investigated invariance of elite subjects kicking a stationary ball with maximum velocity. Such invariance could indicate a:

‘highly sophisticated underlying motor program. […] Variability in some biomechanical parameters and invariance in others could provide insight into the adaptability of the neuromuscular system and the operational interrelationships between mechanical variables.’ (Phillips, 1985)

Phillips (1985) found that experts exhibited greater consistencies than non-experts in ball velocities, ball impact positions, and movement temporal-distance patterns, thus reflecting a ‘highly sophisticated and precisely timed neuromuscular pattern’.

Sforza et al. (2002) investigated the repeatability of a front snap kick by black-belt karateka. Subjects were asked to perform the kick to the chest area and executed the kick with their dominant leg only starting from an informal stance with the feet together. The kick was directed to a reference target which was never touched. The best trained male subjects showed the best repeatability during the execution, which was quantified as the smallest standard deviation in thirteen body landmarks and execution time. Generally, the best repeatability was found in the horizontal plane and for head landmarks, and the worst
in planes representing the direction of movement. Limiting displacement of the head may aid the karateka to maintain balance during the execution of the kick. Athletes with the best repeatability also scored lower standard deviations of paired landmarks of the hips. Again, men showed more symmetry than women. The wrists showed the worst repeatability for all paired landmarks. Sforza et al. (2002) did note that the techniques were performed in a constant environment and that performing them in a less controlled environment as in sparring needs different consideration. In Sforza et al.'s study (2002) the foot is not required to touch the target. Hence, the results only show how consistent the subjects were at missing a target whether the body configuration looked the same whilst doing so. However, for these numbers to be more meaningful they would need to be considered in tandem with the distances of the foot to the target for each trial. Hitting a target like a suspended tennis ball (Sørensen et al., 1996) would not have influenced the kicking action and would still have given a measure of repeatability, whilst also ensuring a real target was hit, thus improving the validity of the results. Any attempted explanation for inter-subject variability is qualified as differences in experience of the subjects. If velocity or force data had been provided, they may have found more quantifiable reasons why certain individuals displayed more variability than others.

Several studies have investigated differences in speed or execution time for the different phases of a kick. Levanon and Dapena (1998) and Nunome et al. (2002) found no marked difference between the duration of the phases of instep kicking and side-foot kicking a soccer ball. Both studies found that foot velocity at ball impact was lower for the side-foot kick which is selected if the ball is to be played more accurately (Levanon & Dapena, 1998). Strategies employed in karate are likely to be different to those followed in the two types of ball kicking and the TKD kicks because little or no energy should be transferred from the leg to the target. Karate athletes execute their kicks at high speeds, 7 to 14 m/s (Feld et al., 1979), even though the kicks need to be exact and controlled, especially when attacking the head (fig. 2.7). To maximise deformation force, a kick should have reached peak velocity at impact (Pieter & Pieter, 1995), which may be expected to be the case for TKD athletes. It will therefore be of interest to compare absolute values and temporal occurrence relative to contact of peak velocities between TKD and karate athletes.
As the two soccer kicks only differ towards the end of their execution, the similarity in duration is not surprising. However, martial arts kicks differ more markedly in their execution. Hong et al. (2000) found significant differences in kicking time, kicking height and muscle activations in different styles of kicks. A turning front kick to the waist level was completed in the shortest time (0.70 ± 0.10 s) and the one-step sidekick to the head took the longest (1.09 ± 0.12 s). Feld et al. (1979) give a range of peak speeds for a number of kicks: the roundhouse kick achieves speeds of 10-11 m/s; the wheel kick achieves speeds of 7-10 m/s; the front kick and the side kick both achieve speeds of 10-14 m/s. Béraud and Gahéry (1995) reported a velocity of 10.3 ± 0.9 m/s when a low roundhouse kick was executed with maximal impact force and 7.0 ± 0.7 m/s when it was executed with minimal impact force.

Kicking studies generally relate to ball kicking and as such are limited to a single kick without much attention to what happens after the ball leaves the foot. In martial arts kicking, what happens after target contact is crucial however, as the athlete may be required to kick or punch again, must maintain an appropriate guard position, or may need to move away from a counter. The literature investigating martial arts kicks has not considered this and has only provided data for single kicks. Whilst these data are clearly important to gain an initial insight into such kicks, it is imperative to investigate their reproducibility and variability if executed in a combination. A mere understanding of single techniques will have limited applicability to skill development for competition. The comparison of training and competition executions should again indicate whether athletes are altering techniques when a successful outcome in minimal time is crucial.
2.2.8 Punching studies

The literature contains a number of punching and striking studies in boxing and martial arts (Walker, 1975; Cavanagh & Landa, 1976; Blum, 1977; Feld et al., 1979; Joch et al., 1981; van Gheluwe & van Schandevijl, 1983; Atha et al., 1985; Chananie, 1999; Pain, 2000; Sforza et al., 2000, 2001). This section focuses on studies that have investigated underlying mechanics of punching, their improvement with training, and their repeatability. It also provides examples of punching speeds from different scenarios and sports.

Zehr et al. (1997) found that karate athletes had advanced elbow extension performance, displaying a greater isometric and ballistic peak torque compared to untrained people. Voight and Klausen (1990) studied the improvement of a karate punch with different training regimes. The subjects whose training included punch bag work showed greater improvements of hand and shoulder velocities indicating that certain training regimes were better than others for improving a specific skill.

Van Gheluwe and Van Schandevijl (1983) looked at the role of the spine in a reverse punch in karate (fig. 2.8) and found lateral and rotational deformation of the spine which started at the hips and migrated up to the shoulders. Their findings showed that karateka do not move the trunk as a solid block when executing this punch, as had been previously believed, but that the movement appeared to be initiated from musculature in the lower body. The progressive rotation of each vertebra affects the spine in a chain-like fashion. Many martial arts teach to generate energy from the waist and hips and 'whip' it up the spinal cord to the upper limbs to strike the opponent. Van Gheluwe and Van Schandevijl’s findings seem to support this theory.

Figure 2.8: Reverse punch. Karateka on the right executes a controlled reverse punch to the head in competition (www.englishkaratefederation.com, 2006)
A number of studies have looked at the breaking potential of karate punches and strikes and several mathematical models have been derived (Walker, 1975; Cavanagh & Landa, 1976; Blum, 1977; Feld et al., 1979; Chananie, 1999). A simple forward punch reaches peak velocity at approximately 70-80% of the total movement (Walker, 1975; Atha et al., 1985). The forward movement of the arm in a punch in the empty air for karate athletes takes 200 ms (Walker, 1975) and peak velocities of such punches have been reported as 7 m/s (Walker, 1975), 5.7-9.8 m/s (Feld et al., 1979) and 7-14 m/s (Blum, 1977). Atha et al. (1985), when looking at a world level heavy-weight boxer, found movement times from initiation to impact of 100 ms and recorded impact velocities of 8.9 m/s when hitting an instrumented target mass. Smith and Hamill (1985) reported fist speeds of approximately 11.5 m/s 10 ms before impact for karate and boxing. If attempting to deliver a punch with maximum effect, a fighter will attempt to coincide the moment of peak velocity at 70-80% of the total movement, with target impact (Pieter & Pieter, 1995). This means that the punching movement will be completed 'inside' the target. The values quoted for techniques thrown into the empty air should therefore be compared to values from impact studies close to or at impact. Joch et al. (1981), recorded an average movement time of 100 ms in boxers if a punch was thrown without a 'wind-up' movement, and showed movement times up to six times greater, if a wind up took place. Pain (2000) stated that in order to cause damage, the fist needs to be as rigid as possible. He argued, however, that if the punch is to be fast as well, there will be a trade-off due to a conflict in muscle recruitment.

Sforza et al. (2000, 2001) investigated the repeatability of a simple static punch where the subjects remained stationary and a dynamic lunge punch in male and female karate black-belts. The punches were performed with the dominant hand only and directed to a reference target at chest level which was not touched. In the first study (2000) with seven subjects, women performed both techniques in a shorter time and with a greater temporal and spatial repeatability than men. In general, relative spatial variability, i.e. of individual landmarks, was lower for the dynamic technique, however, spatial global standard deviations, i.e. of all landmarks, were three to six times higher. Both techniques were found to have the largest kinematic variation in the direction of movement, whereas the smallest variability was displayed in the vertical direction. Similar results were found in the second study (2001) with thirteen subjects. The best individual spatial repeatability was found for three men doing the static technique. Again, women displayed less spatial
variability in their global performance. Largest variability was found in the direction of movement and lowest variability was found in the vertical direction. In the static technique, the hips and shoulders showed the best overall repeatability. In the dynamic technique, the poorest repeatability was in the ankle of the displaced limb. The best repeatability in the dynamic technique was recorded for two women who had been gold medallists (forms) in European and World Championships, indicating that repeatability is linked to experience. The main concern with these two studies as with the kicking study discussed earlier (Sforza et al., 2002) is the fact that the subjects never hit the target and hence the measure of repeatability is related to the degree of missing a reference target, and that no velocity or force data are provided, therefore limiting the biomechanical conclusions that can be inferred from the results.

Studies into punching and striking have been descriptive and therefore have been limited to single techniques. As with kicks, no attempts have been made to investigate the reproduction of punching techniques as parts of martial arts combinations and how this may vary based on different execution modes. This information is clearly important for the athletes and hence merits investigation.

2.2.9 Proximal-distal studies

Kicking, punching and chopping can be regarded as proximal-distal sequence movements (Cavanagh & Landa, 1976; Elliott, 2000). Other examples commonly studied are ball kicking (Roberts et al., 1974; Putnam, 1983, 1991, 1993; Elliott, 2000), baseball pitching (Feltner, 1989; Feltner & Dapena, 1989; Putnam, 1993; Elliott, 2000) and golf-, tennis-, badminton-, baseball- and hockey swings (Putnam, 1993; Elliott, 2000) as well as leg swings in running and walking (Putnam, 1991). This section introduces the theory of proximal-distal movement, gives an account of observations across various sports including martial arts, and illustrates some of the reported mechanics involved in movements comparable to punches and kicks in martial arts.

Although proximal segments do not contribute much kinematically to distal end speed at impact, their motion histories make high distal end speeds possible (Putnam, 1993). There are two main theories on how high distal end speeds are achieved. The principle of optimal coordination of partial moments states that in order to achieve maximum speed at the distal end of an open-linked system, all segments should reach a maximum angular speed at the same time. Although this has been observed in some striking movements, most throwing and striking movements do not conform to this
principle but appear to follow the summation of speed principle, and demonstrate a proximal-distal sequential pattern (Bobbert & van Ingen-Schenau, 1988; Jacobs & van Ingen-Schenau, 1992; Putnam, 1993; van Soest & van Galen, 1995). Generally proximal-distal movement sequences have been described in two ways. When segments at the proximal end of a chain reach their peak velocity and suddenly slow down thereby transferring momentum to the distal segments, the movement has been described as whip-like or a summation (Cavanagh & Landa, 1976). A greater delay in sequencing of muscle activation may allow more energy to be transferred along the kinetic chain (LeBlanc & Dapena, 2002). If active acceleration of distal segments causes the deceleration of proximal segments, the movement has been described as flail-like (Sørensen et al., 1996).

Putnam (1993) explained that when conducting a segment interaction analysis, the number of DoF of the system is equal to the sum of angular DoF at the proximal ends of the segments. Typically, the distal segment lags behind in proximal-distal movement. Comparing ball kicking and baseball pitching, Putnam (1993) described the following similarities across skill. The forward acceleration of the proximal segment and/or the linear acceleration of the proximal end of the distal segment resulted in interactive moments which played a big part in accelerating the distal segment backwards. Following this, the distal segment was accelerated forward by an interactive moment caused by the angular velocity of the proximal segment and by the joint moment at the proximal end of the distal segment. The reduction in forward angular velocity of the proximal segment was mainly due to interactive moments caused by the angular velocity and angular acceleration of the distal segment. Differences across skills were attributed to the timing of segment motions affected by task demands, joint ranges of motion, muscle characteristics or the ways that segments interact.

Putnam (1993) posed that in (ball) kicking the leg is accelerated backwards by an interactive moment caused mainly by the forward rotation of the thigh and to a smaller extent by a knee flexor moment. The distal segment was accelerated forward, causing a decrease in its backward rotation followed by an increase in its forward rotation. The proximal segment was slowed down by interactive moments resulting from the angular velocity and acceleration of the lower leg. Putnam (1983, 1991, 1993) also stated that although a large hip flexor moment was present in kicking, it did not play a role in slowing down the thigh but acted to limit the loss of thigh angular velocity by counteracting the effect of the lower leg's motion on the thigh and concluded that the reduction in the thigh's angular velocity did not serve to increase the angular velocity of the shank, which occurred
as a consequence of the influence of the shank’s angular velocity on the thigh. According to Putnam’s findings (1983, 1991, 1993), the peak knee torque occurred before the peak hip torque. However, Putnam’s findings conflict with other studies (Roberts et al., 1974; Luhtanen, 1988; Elliott, 2000).

Roberts et al. (1974) showed that the accelerations of shank and thigh in ball kicking were out of phase with each other. Contrary to Putnam’s findings (1983, 1991, 1993), maximal knee moment followed that of the hip and it was related in a similar way to peak leg acceleration and rotation reversal. Similar observations were made by Luhtanen (1988) who recorded a hip extensor moment prior to impact and prior to peak knee moment, which was thought to increase the rotational velocity of the leg.

Cavanagh and Landa (1976) described the upper limb movement in a karate chop as ‘a sequential rather than simultaneous extension’ at the shoulder and elbow. They found that shoulder extension was at least 70% complete before elbow extension commenced. They recorded a peak velocity of 9 rad/s of the shoulder, followed 70 ms later by a peak velocity of the elbow of 25 rad/s. They proposed this is a quantitative representation of what others have described as a ‘whip-like’ action or a ‘summation’. Robertson et al. (2004) analysed the kinetics of a front kick in karate and found that a hip extensor moment caused the hip to slow its flexion and initiate knee extension, which they referred to as a whip action, and that knee extensor moments themselves did not contribute to knee extension.

Sørensen et al. (1996) recorded similar findings to Putnam’s (1983, 1991, 1993) for a martial arts high front kick. They examined whether proximal segment deceleration is done actively by antagonist muscles or whether it is a passive consequence of distal segment movement, and whether distal segment acceleration is enhanced by proximal segment deceleration. They did not consider the influence of the torso movement on proximal segment deceleration. Like Putnam, Sørensen et al. (1996) found that thigh deceleration resulted from motion dependent moments from the lower leg and not from its active deceleration. Lower leg acceleration was not enhanced by thigh deceleration. In fact, they reported that thigh deceleration is unavoidable because of lower leg acceleration. Their results led them to adjust the previously defined causal relationship between deceleration of proximal segments and acceleration of distal segments. This had in the past been described as ‘whiplash-like’. However, as distal segment acceleration and velocity cause proximal segment deceleration and not vice versa, they suggested that the term ‘flail-like’ is more appropriate.
Although proximal-distal sequencing studies have been conducted on a wide array of sporting techniques, the relationship between such sequencing and the objective of the technique has not yet been investigated. In this study, similar kicks will be executed in two different ways: one allowing full contact with the target (TKD) and one requiring touch control (karate). Hence, this study will attempt to uncover a link between such sequencing and the control of techniques.

2.2.10 Feedback studies

A number of researchers have recognised the importance of biomechanical feedback to athletes (Newell & McGinnis, 1985; Winter, 1987; Brüggemann et al., 1999; Ae et al., 2005). Scientific studies typically provide ‘cold feedback’ (Ae et al., 2005) as findings will first be processed and subsequently presented in a form that is useful to coaches and athletes. In martial arts training, the most valuable information about movement patterns is still obtained via prescriptive feedback provided by a training partner or coach (Newell & McGinnis, 1985). Qualitative movement analyses and the biomechanical interpretation thereof can provide athletes and coaches with ‘causes and corresponding effect coherences’ for complex martial arts combinations. Winter (1987) suggested that it is essential to establish detailed profiles of biomechanical patterns of excellent athletes, allowing fighters that are training towards elite status to be compared with top martial athletes and an analysis of the differences used to help their development.
2.3 Technical aspects of movement analysis

2.3.1 Three-dimensional movement reconstruction

3D analysis of human movement starts with capturing data using a minimum of two cameras (Allard et al., 1995). The motion capture system used for this study (VICON system) produces 3D data by combining two-dimensional (2D) data from all cameras used in the data capture with calibration data and a set of reconstruction parameters (Oxford Metrics Ltd., 2002b). It uses an algorithm which is company proprietary and no published material is available (personal communication with Sales and Support Manager, Vicon Peak, June 2006).

This study used passive reflective markers to track movement of elite martial athletes. The advantages of such markers are that they allow accurate marking of a point on the body and provide a very high contrast against the background (Greaves, 1995). They are less constraining than active markers, as no wiring or power sources are needed and they are easy to attach to the subject (Pedotti & Ferrigno, 1995). However, their identification requires a more intelligent data processing system especially during ‘critical conditions’ when marker trajectories are lost or overlap. After initial manual labelling using designated software, the system may assign these labels to each marker on a frame-by-frame basis (Pedotti & Ferrigno, 1995). When this cannot be done automatically by the system, the operator must do so manually, which can be a laborious task. A disadvantage of markers, active or passive, that are attached to the skin of a subject is that the movement of the marker may not represent the movement of the underlying bone (Woltring, 1991; Karlsson, 1994; Capozzo, 1996; Fuller et al., 1997; Reinschmidt, 1997). A skin movement artefact with its own coherent structure (Pain & Challis, 2002) and often correlated with the whole limb motion (Woltring, 1991), must be accounted for if the movement of the subject is to be represented (§2.3.2.).

Once the marker data has been converted to 3D, an algorithm is required to extract anatomically useful data from the marker positions. A model is required to estimate and reconstruct JCs and, based on these locations, to define body segments. Only then can the model be used to provide the kinematic and kinetic data for the captured movement.
2.3.2 Methods for the determination of joint centres

Some of the JCs used for this study were determined using a functional method. Hence, a short illustration of the differences between functional and predictive methods of JC estimation is given. Furthermore, the underlying theories of estimating JC using functional methods are explained by progressing from rigid-body methods to methods that account for skin movement artefacts. The two functional methods considered for this study are highlighted, and the limitations of JC determination using any functional method conclude this section.

JCs can be determined using either predictive or functional methods. Predictive methods (Sati, 1994; De Leva, 1996) rely on palpating body landmarks and/or anatomical measurements to estimate JC coordinates. Numerous studies have examined optimal marker placement for estimating the JC locations for different joints (Inman, 1976; Davis et al., 1991; Seidel et al., 1995; Churchill et al., 1998; Stokdijk et al., 1999; Lloyd et al., 2000; Stokdijk et al., 2000). However, identifying landmarks is subjective and failing to do so correctly will lead to incorrect JC approximations. Even with the correct identification of landmarks, inaccuracies in JC location can arise due to scaling and regression errors.

Functional methods calculate JCs based on marker displacement data and therefore avoid the afore-mentioned issues. Mathematical algorithms are applied to estimate the instant centre of rotation (ICR) or an instant axis of rotation (Zatsiorsky, 1998; O’Brien et al., 1999). Several researchers have suggested a range of functional methods to find ICRs in 2D movement and 3D movement (Spoor & Veldpaus, 1980; Grood & Suntay, 1983; Spiegelman & Woo, 1987; Veldpaus et al., 1988; Holzreiter, 1991; Woltring, 1991; Halvorsen et al., 1999; O’Brien et al., 1999; Gamage & Lasenby, 2002; Camomilla et al., 2006; Ehrig et al., 2006). Additionally, researchers have derived suitable algorithms for the optimal placement of markers (Crisco et al., 1994; Holzreiter, 1991, Walter & Panjabi, 1988). However, most validations of functional methods have been done using computer simulations and/or rigid mechanical linkage devices (Halvorsen et al., 1999; Gamage & Lasenby, 2002; Camomilla et al., 2006; Ehrig et al., 2006). Few studies have tested functional methods using human movement data and then only for the hip and shoulder joints (Shea et al., 1997; Bao & Willems, 1999; Leardini et al., 1999; Monnet et al., 2007).

Many functional methods are based on 3D rigid-body movement (Spoor & Veldpaus, 1980; Grood & Suntay, 1983; Veldpaus et al. 1988; Holzreiter, 1991; Woltring, 1991; O’Brien et al., 1999). To describe the movement of a segment in space, the attitude
matrices are obtained from markers attached to that segment (Spoor & Veldpaus, 1980; Veldpaus et al., 1988; Holzreiter, 1991; Woltring, 1991). If $\bar{x}_i$ is the position vector of a marker on the body, the marker distribution for this body is given by the following mean position vector characteristic, where $m$ is the number of markers on the body.

$$\bar{x} = \frac{1}{m} \sum_{i=1}^{m} \bar{x}_i \quad (2.1)$$

This vector gives the location of a point $P_0$ at the centre of the marker distribution. The number of markers must be greater than or equal to three for 3D motion. A further characteristic function is the distribution matrix $[X]$.

$$[X] = \frac{1}{m} \sum_{i=1}^{m} (\bar{x}_i - \bar{x})(\bar{x}_i - \bar{x})^T \quad (2.2)$$

A marker distribution is 3D if all eigenvalues of the distribution matrix differ significantly from zero and the distribution is 2D if the smallest eigenvalue is zero and the remainder differ significantly from zero (Veldpaus et al., 1988).

Veldpaus et al. (1988) state that a rigid-body movement from $t=t_1$ to $t=t_2$ can be represented by the sum of the translation of point $P_0$ described by translation vector $\bar{r}$ and a rotation around $P_0$ described by a rotation matrix $[R]$ which satisfies

$$[R] = [R_1(\alpha) \, R_2(\beta) \, R_3(\gamma)] \quad (2.3)$$

where $\alpha$, $\beta$ and $\gamma$ are the orthogonal angle changes, so that marker positions after movement are given by

$$\bar{x}'_i = \bar{x} + \bar{r} + [R](\bar{x}_i - \bar{x}) \quad (2.4)$$

When applying these rigid-body methods, the question arises to what extent body segments can be modelled as rigid since the markers defining the segment will demonstrate movement artefacts (Woltring, 1991; Karlsson, 1994; Capozzo, 1996; Reinschmidt, 1997).
A procedure is therefore required to minimise the difference between marker movement and the movement of the underlying bone (Veldpaus et al., 1988; Walter & Panjabi, 1988; Crisco et al., 1994; Challis, 1995; O'Brien et al., 1999). Pain and Challis (2002) described soft tissue movement of the forearm in a downward strike and found that the area of each marker sector of a marker array fluctuated up to 1 cm\(^2\) for a resting area of 4 to 7 cm\(^2\). If the marker movement were unrelated to the segment movement, it would be possible to separate out rigid-body movement. However, many such artefacts are significantly correlated with the actual movement (Woltring, 1991) and may not be random but have their own coherent structure (Pain & Challis, 2002).

Rigid-body transformation parameters can be estimated using a weighted least squares (Challis, 1995; Lu & O'Connor, 1999) or an unweighted least squares (Veldpaus et al., 1988) routine. The main difference between these two methods is that for the weighted method the movement of the individual markers is considered to be different from others, whilst for the unweighted method, all markers move in the same way. Other methods employ marker clusters to minimize the effect of skin artefacts but cannot eliminate it fully (Challis, 1995; Andriacchi, 1998; Alexander & Andriacchi, 2000).

Rewriting eq. (2.4) in a simpler form one can say that \( \bar{x}_i \) describes the marker positions on the segment in position 1, \( \bar{x}'_i \) describes the marker positions on the segment in position 2 and \( \bar{r}^* \) the displacement vector between corresponding markers:

\[
\bar{x}'_i = \bar{r}^* + [R] \bar{x}_i
\]  

(2.5)

where \( \bar{r}^* = \bar{x} + \bar{r} - [R] \bar{x} \).

\([R]\) and \( \bar{r}^* \) are unknown and need to be determined from position data (Spoor & Veldpaus, 1980). A measure of the difference of the measured and real positions is given by a function of \( [R] \) and \( \bar{r}^* \) (Spoor & Veldpaus, 1980; Holzreiter, 1991; Challis, 1995).

\[
f(\bar{r}^*, [R]) = \frac{1}{n} \sum_{i=1}^{n} (\langle [R] \bar{x}_i + \bar{r}^* - \bar{y}_i \rangle^T (\langle [R] \bar{x}_i + \bar{r}^* - \bar{y}_i \rangle)
\]  

(2.6)

Measured Real

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Using a least squares method, determining $[R]$ and $\vec{r}^*$ is equivalent to minimising eq. (2.6) (Challis, 1995). This function can be used to estimate the error in the recorded data (Holzreiter, 1991). Holzreiter (1991) warned of two problems when evaluating 3D ICR. Firstly, the movement is often instantaneously planar in which case the ICR is not defined, and secondly, passing through a specific position from different directions may result in different locations for the ICR. The deviation of the measured values to the real values largely depends on the marker distribution, the quality of which can be determined by examining the eigenvalues of the distribution matrix given in eq. (2.2) (Veldpaus et al., 1988).

Methods using a least-square algorithm for calculating the ICR and not assuming rigidity were presented by Halvorsen et al. (1999) and by Gamage and Lasenby (2002). Halvorsen et al.'s (1999) method approximates axes of rotation and JCs in 3D (Camomilla et al., 2006), similar to the midpoint algorithm of Reuleaux in 2D (see Zatsiorsky, 1998). Three points are tracked to find three intersecting planes identifying the ICR at a given time. The method does not assume rigid-body motion, but that each marker rotates around the same fixed axis of rotation or JC. The displacements do not need to be from consecutive time steps and better results are obtained when the displacements are large.

The displacement of marker $j$, $\Delta \vec{r}_j$, is normal to a plane containing the axis of rotation and the midpoint of the line representing the marker displacement (fig. 2.9). For a perfect hinge joint measured under perfect conditions, the projections of the displacements onto the axis of rotation should vanish however in reality, not all projections will vanish. Halvorsen et al. (1999) used these projections to define two objective functions to be minimized. For a spherical joint, the pathways of the markers lie on the surface of a sphere with a radius equal to the distance to the ICR. The intersection of a set of planes, each normal to the displacement and containing the midpoint of the displacement, approximates the ICR. Halvorsen et al. (1999) tackled the problem of locating the ICR in two steps: firstly, they determined the direction of the axis of rotation; secondly, they determined the position of the axis and the ICR.
Figure 2.9: Rotation about a joint in 3D according to Halvorsen et al. (1999) (adapted from Kwon, 2005). Marker j has displacement $\Delta \vec{r}_j = \vec{r}_{jk} - \vec{r}_{ji}$ when moving from time-frame i to k. The intersection of perpendicular lines constructed at the midpoints of such marker displacements approximate the joint location which is given by $\vec{r}_c$.

From figure 2.9 it follows that:

$$ (\vec{r}_{jk} - \vec{r}_{ji}) \cdot \left( \frac{\vec{r}_{jk} + \vec{r}_{ji}}{2} - \vec{r}_c \right) = 0 $$

(2.7)

This applies to the line connecting the ICR and the midpoint of the displacement.

The error function for each marker in eq. (2.7) is given by

$$ e_j = (\vec{r}_{jk} - \vec{r}_{ji}) \cdot \left( \frac{\vec{r}_{jk} + \vec{r}_{ji}}{2} - \vec{r}_c \right) $$

(2.8)

with a cost function $U$

$$ U = \sum_{j=1}^{m} e_j^2 = \left( \frac{\vec{r}_{jk} + \vec{r}_{ji}}{2} - \vec{r}_c \right)^2 $$

(2.9)

with $m$ being the total amount of markers. This equation needs to be minimised (Challis, 1995), to find the best approximation for the JC location, $\vec{r}_c$. 

44
Eq. (2.7) can be rewritten as:

\[ (\vec{r}_{jk} - \vec{r}_{ji})^T \cdot \vec{r}_c = (\vec{r}_{jk} - \vec{r}_{ji})^T \cdot \left( \frac{\vec{r}_{jk} + \vec{r}_{ji}}{2} \right) \]  

(2.10)

or

\[ [A]_{ik} \cdot \vec{r}_c = [B]_{ik} \]  

(2.11)

where \([A]_{ik} = (\vec{r}_{jk} - \vec{r}_{ji})^T\) and \([B]_{ik} = (\vec{r}_{jk} - \vec{r}_{ji})^T \cdot \left( \frac{\vec{r}_{jk} + \vec{r}_{ji}}{2} \right)\).

\(\vec{r}_c\) can be solved by introducing a pseudo inverse of \([A]_{ik}\) to give

\[ \vec{r}_c = ([A]_{ik}^T \cdot [A]_{ik})^{-1} \cdot ([A]_{ik}^T \cdot [B]_{ik}) \]  

(2.12)

Eq. (2.12) can be applied to multiple time-frames and thereby use the whole data set.

Halvorsen et al. (1999) suggested this method produced reasonable results although it was inferior to the rigid-body finite helical axis (HA) method, especially when signal-to-noise ratios were low, but performed better than the HA method when significant skin artefacts were present. The main disadvantage of this method was that problems arose when markers were distributed on a plane that contained the axis of rotation, such displacements between two positions were parallel. This can be avoided if the nature of the motion is known \textit{a priori}.

Gamage and Lasenby (2002) suggested a method (fig. 2.10) for estimating the average centre and axis of rotation similar to Halvorsen et al.’s (1999) approach in that it employs a closed-form least squares algorithm (Kwon, 2005). Gamage and Lasenby (2002) assumed no rigidity but only that the markers remained at a constant distance from the centre or axis of rotation.
From figure 2.10 it follows that the error function in each marker position is given by

\[ \varepsilon_{ji} = (\overrightarrow{r}_{ji} - \overrightarrow{r}_c) \cdot (\overrightarrow{r}_{ji} - \overrightarrow{r}_c) - R_j^2 \]  

(2.13)

where vector \((\overrightarrow{r}_{ji} - \overrightarrow{r}_c)\) is the measured radius of marker \(j\) about the ICR and \(R_j\) is the real radius of marker \(j\). Note that \(\overrightarrow{r}_c\) and \(R_j\) are both unknown.

The cost function for the least squares error of the JC becomes

\[ U = \sum_{j=1}^{m} \sum_{i=1}^{n} \varepsilon_{ji}^2 = \left[ (\overrightarrow{r}_{ji} - \overrightarrow{r}_c) \cdot (\overrightarrow{r}_{ji} - \overrightarrow{r}_c) - R_j^2 \right]^2 \]  

(2.14)

where \(m\) is the total number of markers and \(n\) is the total number of time-frames.

The mean marker position for marker \(j\) is given by

\[ \overrightarrow{r}_j = \frac{1}{n} \sum_{i=1}^{n} \overrightarrow{r}_{ji} \]  

(2.15)

and the relative position of the marker to the mean position at time-frame \(i\) is given by
\[ \Delta_{ji} = \bar{r}_{ji} - \bar{r}_j \]  \hspace{1cm} (2.16)

where by definition the sum over all time-frames of these differences is equal to zero.

From figure 2.2 it also follows that

\[ \bar{p}_j = \bar{r}_c - \bar{r}_j \]  \hspace{1cm} (2.17)

and combining eq. (2.16) with eq. (2.17) yields

\[ \bar{r}_{ji} - \bar{r}_c = \Delta_{ji} - \bar{p}_j \]  \hspace{1cm} (2.18)

This can be substituted back into eq. (2.14) to give

\[ U = \sum_{j=1}^{m} \sum_{i=1}^{n} e_{ji}^2 = \left[ (\Delta_{ji} - \bar{p}_j) \cdot (\Delta_{ji} - \bar{p}_j) - R_j^2 \right] \]  \hspace{1cm} (2.19)

This function needs to be minimised (Challis, 1995) so that

\[ \frac{\partial U}{\partial R_j} = 0 \]  \hspace{1cm} (2.20)

\[ \frac{\partial U}{\partial \bar{p}_j} = 0 \]  \hspace{1cm} (2.21)

From eq. (2.20) it follows that

\[ \frac{\partial U}{\partial R_j} = 0 = \sum_{j=1}^{n} \left[ (\Delta_{ji} - \bar{p}_j) \cdot (\Delta_{ji} - \bar{p}_j) - R_j^2 \right] \]  \hspace{1cm} (2.22)

and from eq. (2.21) it follows that
\[ \frac{\partial U}{\partial \bar{p}_j} = 0 = \sum_{i=1}^{n} (\Delta_{ji} \cdot \Delta_{ji}) \Delta_{ji} - 2 \sum_{i=1}^{n} \Delta_{ji} (\Delta_{ji} \cdot \bar{p}_j) \]  

(2.23)

Reorganising eq. (2.23) and writing the result in matrix form then yields

\[ 2 \frac{1}{n} \sum_{i=1}^{n} \Delta_{ji} \Delta_{ji}^{T} \bar{p}_j = \frac{1}{n} \sum_{i=1}^{n} \Delta_{ji} \Delta_{ji}^{T} \Delta_{ji} \]  

(2.24)

which can be simplified as

\[ [A]_j \bar{p}_j = [B]_j \]  

(2.25)

where \([A]_j = 2 \frac{1}{n} \sum_{i=1}^{n} \Delta_{ji} \Delta_{ji}^{T}\) and \([B]_j = \frac{1}{n} \sum_{i=1}^{n} \Delta_{ji} \Delta_{ji}^{T} \Delta_{ji} \).

Using eq. (2.17) this can then be re-written

\[ [C]_j \bar{r}_c = [D]_j \]  

(2.26)

which can be re-arranged to give an expression for the JC location

\[ \bar{r}_c = [C]^{-1} [D] \]  

(2.27)

In eq. 2.26, \([C]\) is a 3x3 matrix which only requires values for \(\bar{r}_{ji}\) and \(\bar{r}_j\), and \([D]\) is a 3x1 matrix which only requires values for \(\bar{r}_{ji}\). Both \(\bar{r}_{ji}\) and \(\bar{r}_j\) are known from the measured marker displacement data and hence both matrices can be determined.

Gamage and Lasenby (2002) found the method of Halvorsen et al. (1999) to be extremely susceptible to the number of time-frames chosen to calculate vector differences, whilst their method does not suffer this 'defect'. It also performed 'comparably' to the best case of Halvorsen et al. (1999) with regard to systematic skin displacement, but a bad choice of frame difference caused the method of Halvorsen et al. (1999) to perform 'very poorly'. The method of Gamage and Lasenby (2002) is not subject to this as it does not
utilise frame differencing. Although their method 'would not perform well if there is significant radial displacement from the centre or axis of rotation', this also applies to rigid-body motion methods (Gamage & Lasenby, 2002).

Functional methods can only be used in vivo by expressing the marker displacement data in terms of a parent segment (fig. 2.11). Global marker coordinates for the child segment will include movement from other segments and must hence be translated into coordinates of a local parent system, such that any recorded movement will be due solely to the child moving around the parent. The parent segment must be chosen carefully to avoid unwanted movement between this segment and the child.

Figure 2.11: Schematic of 3D rotation. Movement of child segment L from with regard to a parent segment S about joint centre J. Marker displacements of L must be expressed in terms of S rather than in terms of the global coordinate system (G) so that components due to the movement of S can be eliminated.

Researchers have warned that implementing functional methods under 'sub-optimal' conditions may lead to inaccurate estimation of the ICR (Piazza et al., 2004). The accuracy of the results depends on the type of movement used and the range of motion (RoM) of the joint (Camomilla et al., 2006; Siston & Delp, 2006; Begon et al., 2007). The RoM should exceed 15° (Piazza et al., 2001; Camomilla et al., 2006) and a marked improvement in accuracy is obtained with a RoM above 20° or in some cases 45° (Ehrig et al., 2006). Further factors that affect the accuracy of the results are the sample number, the proximity of the marker centroid to the actual JC, the distance between markers (Camomilla et al., 2006) and the signal processing (Chêze, 1995; Begon et al., 2007).
When data processing commenced in this study, the recommended method for functionally determining JCs was that of Gamage and Lasenby (2002) and hence this was employed throughout this investigation. Subsequently, new and potentially improved methods have been suggested. Camomilla et al. (2006) used computer simulation to compare a number of methods including that of Gamage and Lasenby (2002), for estimating the location of the hip JC and recommended the method by Gamage and Lasenby (2002) with the bias compensation by Halvorsen (2003). The bias is compensated by iteratively solving the quartic objective function and using, at each iteration, the previous solution as an initial estimate and introducing a correction term, which incorporates the latter estimate and a model of the photogrammetric error (Camomilla et al., 2006). Ehrig et al. (2006) published a new functional method which they showed was more accurate under certain conditions than existing methods. Although these methods were not available in time to be used in this study, their potential effects on the results are addressed in §7.8.1 and Appendix 4.

### 2.4 Evaluation of the literature

Martial athletes must reproduce complex movement combinations faithfully, especially in competition conditions. Although the literature accounts for studies into movement reproduction and variability, and many aspects of sporting movements including biomechanics, investigations are limited to single techniques and studies usually are of a descriptive nature. Theories of motor control have been explored and tested mostly on non-sporting movements.

This study aims to provide an insight into the control of complex martial arts combinations based on data from elite subjects, and to establish whether the observations can assist in the development of both the elite and aspiring elite athletes. Hence, existing motor control theories and biomechanical observations will be tested on skills consisting of three techniques in two different execution modes. Similarly, movement analysis in this study will be extended to combinations to gain more understanding of the role of variability in complex skill reproduction, and whether skill reproduction in training is representative of that under competition conditions. The study aims to interpret quantitative data with the recognition that a ‘greater integration of research methods of biomechanics and motor control in order to improve effectiveness of biomechanical feedback’ could promote skill enhancement in athletes (Brüggemann et al., 1999).
Chapter 3

METHODS 1–DATA COLLECTION

3.1 Chapter outline

This chapter illustrates the workflow of the data collections. It will present the subjects, the marker sets, and the generic data collection set-up and procedures. The combinations performed by the subjects are described.

3.2 Subjects

Martial athletes from two different disciplines were invited for analyses. The first group consisted of five members of the British TKD national team. The second group were five karate athletes from different backgrounds, all with international fighting experience. Two of these athletes are members of the current English national team affiliated to the WKF and one athlete was until recently a member of the British national team affiliated to the WSKA and the reigning female world champion. Another subject is a former member of the Zimbabwean national team. All ten volunteers (see table 3.1), gave informed consent in accordance with the university’s ethical advisory committee procedures (Appendix 1).

The TKD data collection took place at the start of the second year of this research. The karate data collection took place during the third year of this research after most of the data for TKD had been processed.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>Male</td>
<td>23</td>
<td>168.6</td>
<td>67.5</td>
</tr>
<tr>
<td>TKD2</td>
<td>Female</td>
<td>22</td>
<td>176.6</td>
<td>72.2</td>
</tr>
<tr>
<td>TKD3</td>
<td>Male</td>
<td>19</td>
<td>179.2</td>
<td>63.2</td>
</tr>
<tr>
<td>TKD4</td>
<td>Male</td>
<td>24</td>
<td>177.1</td>
<td>76.1</td>
</tr>
<tr>
<td>TKD5</td>
<td>Male</td>
<td>20</td>
<td>184.5</td>
<td>67.1</td>
</tr>
<tr>
<td>KAR1</td>
<td>Female</td>
<td>30</td>
<td>175.7</td>
<td>68.3</td>
</tr>
<tr>
<td>KAR2</td>
<td>Male</td>
<td>23</td>
<td>172.0</td>
<td>77.1</td>
</tr>
<tr>
<td>KAR3</td>
<td>Female</td>
<td>26</td>
<td>176.3</td>
<td>67.2</td>
</tr>
<tr>
<td>KAR4</td>
<td>Male</td>
<td>21</td>
<td>177.1</td>
<td>71.6</td>
</tr>
<tr>
<td>KAR5</td>
<td>Male</td>
<td>34</td>
<td>167.6</td>
<td>72.6</td>
</tr>
</tbody>
</table>
3.3 Experiment set-up

The TKD data collection took place over two days in the Gymnastics Centre at Loughborough University. The athletes performed their combination on a section of the vaulting track which was 4.5 m in length and 1.5 m in width. The surface of the vaulting track consists of concrete which is covered by a 35 mm mat.

![Figure 3.1: TKD experimental layout. 3D capture system cameras are shown in red, three of which were mounted on tripods and nine were clamped to the banister of the Gymnastics Centre at Loughborough University. High-speed cameras are shown in yellow. A stick figure representation of a subject is positioned in the 4.5 by 1.5 m area the TKD combination was performed in and the global coordinate system is represented.](image)

Twelve cameras were positioned to fully capture the area in which the combination was performed (fig. 3.1). Three cameras were offset to each other to the left of this area and were mounted on tripods. The remaining cameras were all mounted on clamps on the railing of the balcony overlooking the gymnastics area at a height of approximately 5.6 m from the concrete floor under the mat. Three of these cameras were positioned to the back of the athlete, three to the right, and the remaining three to the front.

Two high-speed video cameras were positioned to the right of the subject. One was positioned at right angles to the direction of movement and the other was positioned at an angle so it could capture the technique as it progressed forwards. On day two of the data collection, a DV camera was placed to the right of the subjects, footage of which was used purely for reference purposes. Figure 3.1 shows the positions of the 3D motion capture system.
cameras in red and the high-speed cameras in yellow. It also shows the global coordinate system as well as a representation of the area the combination was performed in. A stick figure of the subject is positioned inside this area. The motion capture system was set up and calibrated to collect movement data at 250 Hz.

The karate data collection took place on one day in the Sports Biomechanics Research Laboratory of Loughborough University. Three martial arts mats were placed on the floor to form a section which was approximately 4.5 m in length and 1.5 m in width (fig. 3.2). As the department had upgraded its motion capture equipment, data could now be captured at 480 Hz and still view a capture volume large enough for the study. Ten cameras were used: eight cameras were fitted to brackets on the walls of the laboratory and two cameras were fitted to tripods towards the left rear and right front of the athletes to cover lower angles of the skill. A high-speed camera was placed in a high position to the right of the combination. Figure 3.2 shows the positions of the 3D motion capture cameras in red and the high-speed camera in yellow. It also shows the global coordinate system as well as a representation of the area the combination was performed in. Additional footage for reference purposes only was recorded using a DV camera.

![Figure 3.2: Karate experimental layout. 3D capture system cameras are shown in red, two of which were mounted on tripods and nine were mounted on brackets on the wall of the Sport Biomechanics Research Laboratory Loughborough University. A high-speed camera is shown in yellow. A stick figure representation of a subject is positioned in the 4.5 by 1.5 m area the karate combination was performed in and the global coordinate system is represented.](image-url)
For both TKD and karate high speed video was recorded at 400 Hz. These data were used for detailed observation of the movements and was provided to the TKD squad performance manager and to individual karate athletes.

3.4 Marker set

For the TKD data collection a redundant marker set of fifty retro-reflective passive markers of 25 mm diameter were attached to the subjects for the static and subject set-up trials. Once these trials had been completed, superfluous markers were removed, leaving forty markers, so the subject could perform the combination with minimum inhibition from the markers. The full marker set entitled *Fighter* is based on an example given in the VICON Preparation Manual (Oxford Metrics Ltd., 2002c) and is given in table 3.2. An explanation of how the full marker set was used will be given in §4.4.7. The non-bold markers could be arbitrarily placed on the segment and were removed for the combination. For the karate data collection one additional marker was positioned laterally on the foot near metatarsal 5, as it was observed during the TKD data analysis that the toe marker disappeared more than anticipated. During the karate data collection, markers on the tibia and forearm were not used as they were only needed to functionally determine the elbow and knee JC locations. Results from the earlier TKD data collection showed that no realistic locations could be found for these JC. Hence, the full karate marker set consisted of forty-eight markers.
## Table 3.2: the Fighter marker set

<table>
<thead>
<tr>
<th>Marker</th>
<th>Definition</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFHD</td>
<td>Left front head</td>
<td>Left temple</td>
</tr>
<tr>
<td>RFHD</td>
<td>Right front head</td>
<td>Right temple</td>
</tr>
<tr>
<td>LBHD</td>
<td>Left back head</td>
<td>Left back of head</td>
</tr>
<tr>
<td>RBHD</td>
<td>Right back head</td>
<td>Right back head</td>
</tr>
<tr>
<td>C7</td>
<td>7th cervical vertebra</td>
<td>Base of the neck</td>
</tr>
<tr>
<td>T10</td>
<td>10th thoracic vertebra</td>
<td>Centre mid-back</td>
</tr>
<tr>
<td>LUM1</td>
<td>1st lumbar vertebra</td>
<td>Lower back</td>
</tr>
<tr>
<td>CLAV</td>
<td>Clavicle</td>
<td>Top of the breast bone</td>
</tr>
<tr>
<td>STRN</td>
<td>Sternum</td>
<td>Base of the breast bone</td>
</tr>
<tr>
<td>RBAK</td>
<td>Right back</td>
<td>Centre of the right shoulder blade</td>
</tr>
<tr>
<td>LSHO</td>
<td>Left shoulder</td>
<td>Placed on the bony prominence on top of the left shoulder</td>
</tr>
<tr>
<td>LSHF</td>
<td>Left shoulder front</td>
<td>Placed on the front of a visually determined frontal axis through the shoulder ball-and-socket joint</td>
</tr>
<tr>
<td>LSHB</td>
<td>Left shoulder back</td>
<td>Placed on the back of a visually determined frontal axis through the shoulder ball-and-socket joint</td>
</tr>
<tr>
<td>LUPA</td>
<td>Left upper arm</td>
<td>Placed on the outside of the upper arm</td>
</tr>
<tr>
<td>LUPB</td>
<td>Left upper arm 2</td>
<td>Placed on the outside of the upper arm offset to LUPA or on inside of the elbow joint</td>
</tr>
<tr>
<td>LELB</td>
<td>Left elbow</td>
<td>Placed on the bony prominence on the outside of the elbow joint</td>
</tr>
<tr>
<td>LFRA</td>
<td>Left forearm</td>
<td>Placed on the outside of the lower arm (TKD only)</td>
</tr>
<tr>
<td>LWRA</td>
<td>Left wrist</td>
<td>Extended from the thumb side using a wrist bar</td>
</tr>
<tr>
<td>LWRB</td>
<td>Left wrist</td>
<td>Extended from the little finger side using a wrist bar</td>
</tr>
<tr>
<td>LFIN</td>
<td>Left finger</td>
<td>Placed just below the middle knuckle on the left hand or on the mitt</td>
</tr>
<tr>
<td>RSHO</td>
<td>Right shoulder</td>
<td>Placed on the bony prominence on top of the left shoulder</td>
</tr>
<tr>
<td>RSHF</td>
<td>Right shoulder front</td>
<td>Placed on the front of a visually determined frontal axis through the shoulder ball-and-socket joint</td>
</tr>
<tr>
<td>RSHB</td>
<td>Right shoulder back</td>
<td>Placed on the back of a visually determined frontal axis through the shoulder ball-and-socket joint</td>
</tr>
<tr>
<td>RUPA</td>
<td>Right upper arm</td>
<td>Placed on the outside of the upper arm</td>
</tr>
<tr>
<td>RUPB</td>
<td>Right upper arm 2</td>
<td>Placed on the outside of the upper arm offset to RUPA or on inside of the elbow joint</td>
</tr>
<tr>
<td>RELB</td>
<td>Right elbow</td>
<td>Placed on the bony prominence on the outside of the elbow joint</td>
</tr>
<tr>
<td>RFRA</td>
<td>Right forearm</td>
<td>Placed on the outside of the lower arm (TKD only)</td>
</tr>
<tr>
<td>RWRA</td>
<td>Right wrist</td>
<td>Extended from the thumb side using a wrist bar</td>
</tr>
<tr>
<td>RWRB</td>
<td>Right wrist</td>
<td>Extended from the little finger side using a wrist bar</td>
</tr>
<tr>
<td>RFIN</td>
<td>Right finger</td>
<td>Placed just below the middle knuckle on the left hand or on the mitt</td>
</tr>
<tr>
<td>Marker</td>
<td>Definition</td>
<td>Position</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>LASI</td>
<td>Left anterior super iliac</td>
<td>Bony protrusion of the anterior super iliac</td>
</tr>
<tr>
<td>RASI</td>
<td>Right anterior super iliac</td>
<td>Bony protrusion of the anterior super iliac</td>
</tr>
<tr>
<td>LPSI</td>
<td>Left posterior super iliac</td>
<td>Dimples created by the posterior super iliac</td>
</tr>
<tr>
<td>RPSI</td>
<td>Right posterior super iliac</td>
<td>Dimples created by the posterior super iliac</td>
</tr>
<tr>
<td>LHIP</td>
<td>Left hip</td>
<td>Placed laterally on top of the ilium</td>
</tr>
<tr>
<td>RHIP</td>
<td>Right hip</td>
<td>Placed laterally on top of the ilium</td>
</tr>
<tr>
<td>LTHI</td>
<td>Left thigh</td>
<td>Placed on the thigh</td>
</tr>
<tr>
<td>LTH2</td>
<td>Left thigh 2</td>
<td>Placed on the thigh offset to LTHI or on inside of the knee joint</td>
</tr>
<tr>
<td>LKNE</td>
<td>Left knee</td>
<td>Placed on the outside of the knee joint</td>
</tr>
<tr>
<td>LTIB</td>
<td>Left tibia</td>
<td>Placed on the shin (TKD only)</td>
</tr>
<tr>
<td>LANK</td>
<td>Left ankle</td>
<td>Placed on the bony prominence on the outside of the ankle</td>
</tr>
<tr>
<td>LHEE</td>
<td>Left heel</td>
<td>Placed on the back of the foot</td>
</tr>
<tr>
<td>LTOE</td>
<td>Left toe</td>
<td>Placed centrally on the base of the toes</td>
</tr>
<tr>
<td>LSOF</td>
<td>Left lateral side of foot</td>
<td>Placed laterally to MT5 (karate only)</td>
</tr>
<tr>
<td>RTHI</td>
<td>Right thigh</td>
<td>Placed on the thigh</td>
</tr>
<tr>
<td>RTH2</td>
<td>Right thigh 2</td>
<td>Placed on the thigh offset to RTHI or on inside of the knee joint</td>
</tr>
<tr>
<td>RKNE</td>
<td>Right knee</td>
<td>Placed on the outside of the knee joint</td>
</tr>
<tr>
<td>RTIB</td>
<td>Right tibia</td>
<td>Placed on the shin (TKD only)</td>
</tr>
<tr>
<td>RANK</td>
<td>Right ankle</td>
<td>Placed on the bony prominence on the outside of the ankle</td>
</tr>
<tr>
<td>RHEE</td>
<td>Right heel</td>
<td>Placed on the back of the foot</td>
</tr>
<tr>
<td>RTOE</td>
<td>Right toe</td>
<td>Placed centrally on the base of the toes</td>
</tr>
<tr>
<td>RSOF</td>
<td>Right lateral side of foot</td>
<td>Placed laterally to MT5 (karate only)</td>
</tr>
</tbody>
</table>
Figure 3.3 shows the markers attached to a subject on TKD day 1. Figure 3.4 shows them attached to a different subject on TKD day 2. On day 2, markers LUPB, RUPB, LTH2 and RTH2 were placed on the medial sides of the elbow and knee joints. This allows for an estimate of the elbow and knee JC's by calculating the midpoint of the relevant markers placed. This was also done for the karate data collection. For the karate subjects two extra markers were placed on the feet as shown in figure 3.5.
3.5 Movement data collection

For all subjects three different trial types were captured. Firstly, a single time-frame from a static trial was used to create local coordinate systems for JC reconstruction. This was followed by a number of subject set-up trials to provide movement data to functionally determine JC locations. For the shoulder and hip joints, the subjects performed a star-arc movement (Camomilla et al., 2006). For the elbow and knee joints, flexion, extension and circumduction were performed. As this study also required information on the movement of central segments, the subjects performed trials to determine movement sections of the spine which were repeated several times with full voluntary range of motion (RoM): bend forward and back; bend laterally in both directions; and longitudinally rotate in both directions. Static trials were recorded for ten seconds. Subject set-up trials were continued until a minimum of five repetitions of the prescribed movements had been completed. Motion capture data were recorded at 250 Hz for TKD and 480 Hz for karate. Finally, the subjects were allowed a ten-minute warm up before performing the martial combinations described below. These trials are referred to as dynamic trials.

Figure 3.5: Marker set on karate subject
3.6 Martial combination descriptions

The subjects performed an attacking combination consisting of three techniques. It was conditional that the subjects were competent in using this combination effectively in competition. To ensure that this was the case for TKD, the performance director and the coach of the Great British TKD team were consulted with regard to selecting a popular combination that fitted within the constraints of the current research set-up. As a result the following technique was chosen: *Slide front leg turning kick; followed by a back leg turning kick; followed by a back leg jumping turning kick* (fig. 3.6). The aim of the TKD combination is to drive the opponent backwards with kick 1, kick 2 should then be used to attempt a score whilst the opponent is parrying and moving back from the first kick, and kick 3 should aim to score again whilst being in the air in order to avoid a counter score.

Figure 3.6: TKD combination A. slide front leg turning kick; B. back leg turning kick; C. back leg jumping turning kick
The karate combination was chosen by a karate coach as a popular attacking combination which most fighters use: *shuffle forward front hand jabbing punch to the head; followed by a shuffle forward back hand reverse punch to the body; followed by a step up front leg round-house kick to the head* (fig. 3.7).

A.

B.

C.

Figure 3.7: Karate combination A. front hand jab; B. back hand reverse punch; C. front leg round-house kick
The aim of the karate combination is to first catch the opponent by surprise and then drive them into a position for a high scoring kick. The aim of the first punch in the combination is to catch the opponent by surprise, get within their space and move their guard up and possibly score. As the opponent starts to move back, hopefully exposing the body, the second punch aims to drive deep into the body covering a lot of distance. If this does not result in a score due to the opponent moving back and getting the torso out of the way, their guard should have dropped and they should now be in range for the high scoring kick.

Subjects performed their combination in two different modes: normal and 100%. Subjects were instructed to perform a number of trials in 'normal mode representing a training maximum execution, ensuring the execution was technically as correct and accurate as possible as typically done in advanced skill honing practice. Once the normal trials had been recorded, the subjects were asked to perform their combinations in 100% mode representing a competition maximum, executing these trials in such a manner that scoring was absolutely imperative within a minimum amount of time. For both execution modes, trials were captured until at least five adequate captures for TKD and ten for karate had been recorded in each mode. Previous studies examining kinetics of martial arts kicks had typically used data from three to five trials per subject (Sørensen et al., 1996; Robertson et al., 2004). For TKD motion capture data was recorded at 250 Hz and for karate at 480 Hz. In both cases, high speed video was recorded at 400 Hz. DV data were recorded at 50 Hz.

Subjects had to aim their techniques at two target pads which were held by a second person, who was also a martial athlete in the respective sport and familiar with the combination. The target consists of a standard focus pad fitted with a force transducer and readout display. For the TKD data collection, one marker was fitted to the top of each pad. Two additional markers were fitted laterally to each pad for reference purposes in the karate data collection.
3.7 Anthropometric data collection

Various researchers have suggested models to estimate inertial properties of the human body (Jensen, 1976; Hatze, 1980; Zatsiorsky & Seluyanov, 1983; Yeadon & Morlock, 1989; Yeadon, 1990; Challis & Kerwin, 1992).

In this study, subject specific inertial parameters were calculated using the geometric model proposed by Yeadon (1990), which uses stadium shapes to approximate forty sections of the body. A total of ninety-five anthropometric measurements as well as the height and weight of the subject were required for the model which an experienced person recorded in twenty to thirty minutes per subject. All the recorded anthropometric data can be found in Appendix 3, §A3.1.
Chapter 4

METHODS 2 – DATA PROCESSING

4.1 Chapter outline

This chapter describes the practical and theoretical tools used in data processing. The details of using a 3D motion capture system and considerations in the design of a whole-body model for implementation of functional JCIs are presented. A stepwise guide through the data processing procedures is then outlined.

4.2 Acquisition of movement data

For this study, a 3D motion capture system using passive retro-reflective markers was employed. These retro-reflective markers were attached to specific body landmarks on a subject and their positions were recorded using specialist cameras (fig. 4.1). Each camera unit consists of a video camera, a strobe head assembly, a lens and an optical filter. The strobe head assembly is a ring of infrared light emitting diodes (LEDs). This infrared light is reflected by the body markers and hits the lens of the camera.

![Figure 4.1: Example of a 3D motion capture camera (adapted from Oxford Metrics Ltd., 2002d)](image)

Before movement data capture, the motion analysis system needed to undergo two calibration steps. The first was a static calibration where a calibration object was placed in
the capture volume and the system recorded the object. For this study, the static calibration was performed using the Ergocal calibration frame with four 25 mm markers. The second was dynamic calibration where a different calibration object was moved through the capture volume for a period of time. For this study this was an Ergocal 390 mm length wand fitted with three 25 mm markers. The 3D motion capture system recorded the movement and using data from both steps the system calculated the errors in each camera. If the calibration result is not acceptable, the locations and settings of each camera are altered and calibration is repeated.

Table 4.1 shows the calibration values obtained for the TKD data collection. An average camera residual of just over 2 mm was obtained on both days. The residual is the root mean square of the distance between a ray from the centre of the strobe ring to the centroid of the marker and the location on the lens where the strobe ray reflected from the marker centroid hits.

Table 4.1: TKD calibration values

<table>
<thead>
<tr>
<th>Camera</th>
<th>Day 1 Residual (mm)</th>
<th>Day 2 Residual (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.282</td>
<td>1.525</td>
</tr>
<tr>
<td>2</td>
<td>1.944</td>
<td>2.131</td>
</tr>
<tr>
<td>3</td>
<td>1.656</td>
<td>1.345</td>
</tr>
<tr>
<td>4</td>
<td>2.923</td>
<td>2.211</td>
</tr>
<tr>
<td>5</td>
<td>2.178</td>
<td>1.990</td>
</tr>
<tr>
<td>6</td>
<td>2.655</td>
<td>2.426</td>
</tr>
<tr>
<td>7</td>
<td>2.051</td>
<td>1.873</td>
</tr>
<tr>
<td>8</td>
<td>1.790</td>
<td>1.479</td>
</tr>
<tr>
<td>9</td>
<td>2.461</td>
<td>2.389</td>
</tr>
<tr>
<td>10</td>
<td>2.328</td>
<td>2.245</td>
</tr>
<tr>
<td>11</td>
<td>2.292</td>
<td>2.336</td>
</tr>
<tr>
<td>12</td>
<td>2.384</td>
<td>2.408</td>
</tr>
</tbody>
</table>

Mean residual (std. dev.) 2.245 (0.341) 2.030 (0.373)
Residual Range (high-low) 1.268 (2.923-1.656) 1.081 (2.426-1.345)

Table 4.2 shows the calibration values for the karate data collection. The mean residual of approximately 0.6 mm is markedly lower than that in the TKD calibrations. The two main reasons for this are that the cameras in the biomechanics laboratory were much closer to the capture volume than those in the Gymnastics Centre (see §3.3) and secondly the motion capture system had been upgraded before the karate data collection.
Table 4.2: Karate calibration values

<table>
<thead>
<tr>
<th>Camera</th>
<th>Residual (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.688</td>
</tr>
<tr>
<td>4</td>
<td>0.612</td>
</tr>
<tr>
<td>5</td>
<td>0.536</td>
</tr>
<tr>
<td>6</td>
<td>0.548</td>
</tr>
<tr>
<td>7</td>
<td>0.674</td>
</tr>
<tr>
<td>8</td>
<td>0.571</td>
</tr>
<tr>
<td>10</td>
<td>0.803</td>
</tr>
<tr>
<td>11</td>
<td>0.617</td>
</tr>
<tr>
<td>12</td>
<td>0.697</td>
</tr>
<tr>
<td>13</td>
<td>0.667</td>
</tr>
</tbody>
</table>

Mean residual (std. dev.) 0.641 (0.077)
Residual Range (high-low) 0.267 (0.803 - 0.536)

4.3 Preparation of movement data

4.3.1. Reconstructions

Once the system had been calibrated, movements of interest could be captured. The system uses the 2D information from each camera to make a 3D reconstruction of the movement. Settings yielding the best reconstruction, e.g. less flickering and jumping of markers, were subjectively chosen, using a trial-and-error approach.

4.3.2. Labelling

Once 3D data had been reconstructed, all the markers were labelled using the labelling software. A time-frame in which all markers were clearly visible was chosen as a starting point and the most productive approach was found to be labelling a complete structure, e.g. the pelvis, and then checking the whole trial to confirm those markers. Markers that were occluded during part of a trial required relabelling and their trajectories defragmenting. Gaps in a trajectory can generally be filled in two ways: a spline-fill can be used or a trajectory from another marker can be copied to fill the gap. Great care must be taken using these methods and the nature of the movement around the gap must be taken into account. Where there are sudden reversals or impacts, a spline-fill would result in unrealistic marker positions. Also when a gap is very large a spline fill may not be appropriate. It may be better to copy similar trajectories of markers placed on the same segment in such cases. Bearing this in mind, it is possible to pre-empt problematic marker positions and place additional markers in close proximity. In this study, extra markers were placed on the pelvis and, during the karate data collection, on the feet. For a few trials during the TKD study no adequate trajectories could be copied for the toe marker.
which disappeared temporarily at critical instances after target contact of a kick. In such cases, a trajectory from another foot marker, e.g. the ankle, was applied and then the position curves were manually adjusted based on the high-speed video footage and other trials in which the toe marker remained visible throughout to yield an acceptable trajectory.

4.3.3. Filtering

After all gaps had been filled the motion data was filtered using quintic splines (Woltring, 1986). It is essential to smooth position data prior to using it since noise is amplified on differentiation to calculate velocities or accelerations (Challis & Kerwin, 1996; van den Bogert, 1996). The degree of filtering was set based on a predicted Mean Square Error (MSE) value between the spline fit and the actual data. The filtering of movement data around impacts is problematic since the impact is likely to contain higher frequencies of both noise and signal than the remainder of the data. Ideally, therefore, impact data should be filtered separately. For the purposes of this study, data leading up to and beyond contact, needed to be looked at as a whole. Hence, it would not have been appropriate to separate the data and a criterion for filtering the whole trial needed to be established.

The MSE value for each subject's dynamic trials was chosen by careful inspection of the movement sequence. Firstly, the data had to be filtered sufficiently so that the markers did not 'jump' when they should essentially be still. Secondly, the data should not be over-smoothed such that characteristics of sudden movement reversals and impacts were lost. Although this required a certain amount of subjective interpretation, in order to retain as much objectivity as possible, the settings were chosen as follows: for a given trial, the distance between two or three markers on the same segment and their positions relative to the global origin were plotted, together with the top target pad marker acceleration. A filter setting was then chosen that produced smooth curves for the position data, whilst not reducing the acceleration peaks of the pad marker by more than 10%. For karate trials the accelerations of the pad for the kick were used, as this is the technique which is the most crucial in terms of controlling its impact. For all subjects the MSE value was determined by choosing the best option based on this visual inspection of the smoothed marker data (Woltring, 1995; van den Bogert, 1996).

The static trials and dynamic trials were filtered using separate settings due to the differing frequency contents. For each subject, a different MSE value was considered for
the static and dynamic trials for the combination. Table 4.3 shows the various filter-settings for the subjects and the static and dynamic trial types.

The raw marker data of the subject set-up trials were exported and filtered using a two way zero lag fourth order filtering routine with a cut-off frequency of 6 Hz. This was done in order to ensure that high frequency signals were removed rather than spline fit which may leave certain artefacts, as the marker movements needed to be representative of the child movement in order to be able to approximate the JC locations.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Static Trial MSE</th>
<th>Dynamic Trial MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>0.20</td>
<td>5.00</td>
</tr>
<tr>
<td>TKD2</td>
<td>0.20</td>
<td>7.00</td>
</tr>
<tr>
<td>TKD3</td>
<td>0.20</td>
<td>7.00</td>
</tr>
<tr>
<td>TKD4</td>
<td>0.20</td>
<td>10.00</td>
</tr>
<tr>
<td>TKD5</td>
<td>0.20</td>
<td>6.00</td>
</tr>
<tr>
<td>KAR1</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>KAR2</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>KAR3</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>KAR4</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>KAR5</td>
<td>0.20</td>
<td>0.25</td>
</tr>
</tbody>
</table>

It is clear that the MSE values for the TKD subjects were much higher than those for the karate subjects. This is most likely due to the nature of the techniques. As the TKD subjects aimed to impact the pads as hard as possible, they may have caused much higher acceleration peaks. The karate subjects were aiming for touch control and hence the accelerations were lower. In order to not reduce the acceleration peaks by more than 10% these MSE values were therefore very low.

4.4 Processing of marker data

4.4.1. Modelling and exporting data

The data could now be used in a model to convert the marker information into kinematic and kinetic data. For this study a whole-body model was written using the software included with the 3D motion capture system. In brief, the model defines segments based on three markers and computes Euler angles between segments. Subject specific inertia values were input for each segment. The output from the model consisted
of the joint angle and moment time histories. A detailed description of the model is given below.

**4.4.2. Fighter model segment definitions**

The marker set described in §3.3 was used to create a fourteen segment representation of the martial athlete based on careful consideration of the movements the model must represent and the required output quantities. A three-segment leg consisting of a femur, a tibia and a foot was used. The arm is represented by two segments: the humerus and the forearm-and-hand segment with no separate hand as it is fair to assume that in punching the wrist is kept rigid.

The central segments demanded closer attention. During kicking combinations particularly, the spine undergoes a number of rotations. In reality the spine can be divided into motion segments, where the motion of each segment is coupled with the next, each of which has six DoF, due to the intervertebral disk's ability to deform, rotate and translate (Zatsiorsky, 1998). However, the spine as a whole can produce only flexion-extension, lateral flexion and axial rotation. The flexibility of the spine varies along its length. Movement of the thoracic spine is restricted in flexion-extension and lateral bending due to thin intervertebral disks, configuration of the articular facets, and the apposition of the spinous processes (Zatsiorsky, 1998). Due to its thicker intervertebral disks, the lumbar region allows large flexibility in flexion-extension and lateral bending, but axial rotation is restricted due to the articular facets (Zatsiorsky, 1998). The cervical region demonstrates three DoF due to the occipital-atlanto-axial complex which has two rotational DoF and the atlas which can move independently (Zatsiorsky, 1998). Since the study is interested in what biomechanical differences occur throughout the body it is imperative that the central segments are represented in sufficient detail.

Initially, it was considered to represent the core of the body by five segments: a head; a cervical spine; a thoracic spine; a lumbar spine; and a pelvis. However, inspection of the range of movement trials comprising flexion and extension, lateral bending, and axial rotation of the spine revealed that no distinguishable movement occurred between the head and the cervical spine, hence these were represented by a single segment resulting in the fourteen-segment *Fighter* model depicted in figure 4.2a with a more detailed schematic of the central segments in figure 4.2b.
The segments in figure 4.2 have been named as follows:

- Head & Neck
- Trunk (comprised of the upper and lower back)
- Upper back
- Lower back
- Pelvis
- Left thigh
- Right thigh
- Left shank
- Right shank
- Left foot
- Right foot
- Left humerus
- Right humerus
- Left forearm
- Right forearm

Martial arts techniques are very explosive and it is likely that the RoM of certain joints is greater than observed in other sporting movements. Hence, all segments were defined independently and connected using ball-and-socket joints, allowing angle changes about three axes. This orthogonal representation of the segment axes is unlikely to
conform to a joint's natural axes. Although one or sometimes two segment axes were defined to best represent natural joint axes, it is unlikely that they coincide fully. Hence, restricting the independent axes of segments comprising a joint would have removed information of movement in that joint. The next few paragraphs elaborate on the implementation of these considerations.

The *Fighter* model was written in BodyLanguage (Oxford Metrics Ltd., 2002a) (Appendix 2, §A2.3) and is based on one of the standard models supplied with the employed motion capture system.

The model is used for the computation of both kinematics and kinetics. These calculations primarily rely on the segment definitions, and hence it is important that JC locations bounding the segments are defined as accurately as possible. To adequately represent the martial arts movements of this study the segment definitions need to allow the necessary independence. The simplifications made in the original model, which was designed for gait analysis, were not appropriate for the movements investigated in this study and the *Fighter* model differs from the original in two important ways.

Firstly, the *Fighter* model creates two separate representations of the body. This means that the segments based on the predictive JC definitions can be compared to those based on JC locations constructed using alternative functional methods which were established *a priori*. These JC locations are recalled into temporary segment definitions based on markers which remain throughout the dynamic trials and should be chosen in such a way that skin and soft tissue movement is minimal at their attachment sites. Other more complex considerations regarding the coordinate system in which to reconstruct JC locations have been outlined in §7.8.1 and Appendix 4. The routines designed to do this are described in detail in §4.4.7.

Secondly, the segment definitions in the *Fighter* model have been changed from the original definitions in such a way that each segment is completely independent. In the original model, some segments are constructed using one or two of the same markers which restricts the motion that can be recorded about the joint between them.

To describe the movement of a segment in space, its attitude matrices need to be obtained (Spoor & Veldpaus, 1980; Veldpaus et al., 1988; Holzreiter, 1991; Woltring, 1991). A minimum of three markers is required to define a segment and using more than three markers is generally impractical during athletic movement as it can affect the subject's freedom of movement, markers are likely to be occluded, sites to affix the markers to are limited, and fourteen segments need to be tracked at any time. Two markers
define the first axis of the coordinate system. One of these markers is then used together with the remaining marker to determine a defining line. The cross product of this line and the first axis forms the second axis of the coordinate system. Both axes are normalised and determine the third axis using the right hand rule (fig. 4.3).

\[
\vec{i} \times \vec{j} = \vec{k} \tag{4.1}
\]
\[
\vec{j} \times \vec{k} = \vec{i} \tag{4.2}
\]
\[
\vec{k} \times \vec{i} = \vec{j} \tag{4.3}
\]

Figure 4.3: Segment creation using three markers. A vector from marker A to marker B forms the x axis, the cross product of a vector from marker A to marker C and the x axis forms the z axis and the right hand rule forms the y axis, with the origin at A.

4.4.3. Fighter model axes and angle definitions

In the Fighter model, the segment axes have been defined with the positive z-axis as the longitudinal axis from the proximal to the distal end for the limbs and from top to bottom for central segments (fig. 4.4). The positive y-axis is the transverse axis pointing to the subject’s right, and the positive x-axis is the frontal axis pointing to the subject’s front.

Angle changes are calculated using Euler or cardan angles and represent changes about the first parent axis, the second floating axis and the last child axis such that the first rotation (y) pertains to flexion-extension, the second (x) to abduction-adduction or valgus-varus rotation and the third (z) to longitudinal rotation respectively.
Parent and child segments were defined independently in order to preserve as much angle information as possible and in such a way that angle changes for all the possible anatomical movements of the segment are represented, e.g. the inclusion of a wrist marker in the definition of the forearm segment allows for pronation and supination when examining angles between the humerus and the forearm. If two segments share a defining line, certain angle information is lost. This means that the angles changes between these segments may not account for the actual movement that occurs. If the segments share an axis, the movement that can be described is even more restricted.

In the *Fighter* model flexion, abduction or valgus rotation, and internal rotation are defined as positive (fig. 4.5); extension, adduction or varus rotation, and external rotation are defined as negative (fig. 4.6).
Figure 4.6: Examples of negative rotation of the limbs in the *Fighter* model – extension of knee (a); elbow (b); hip (c); adduction of shoulder (d); hip (e); external rotation hip (adapted from Barua & Roosen, 2005)

For the central segments forward flexion is defined as positive. When viewed from the front anticlockwise rotation of the child segment, i.e. left flexion of the subject if child is below parent, has been defined as positive (fig. 4.7) and when viewed from the top clockwise rotation has been defined as positive (fig. 4.8).

Figure 4.7: Lateral rotation for central segments in the *Fighter* model - child C rotates about the frontal axis of parent P viewed from the front. Anticlockwise rotation is positive and results in left flexion of the body; clockwise rotation is negative and results in right flexion.
4.4.4. Fighter model kinetic hierarchy definition

In order to compute kinetic information a kinetic hierarchy must be defined using connection points between segments. If a segment has no connection point and therefore no parent segment it is considered a root segment (Oxford Metrics Ltd, 2002a). The BodyLanguage restricts each segment to having only one parent segment (Oxford Metrics Ltd, 2002a). For the limbs, the JC locations are used as connection points. Central segments are connected using three virtual JCs:

- TOPJC connects the head-and-neck segment to the upper back segment and was approximated by a vector originating in the C7 marker (table 3.2) with a direction from the centre of the back of the head markers to the centre of the front of the head markers and a magnitude of an eighth of said vector;
- MIDJC connects the upper back segment to the lower back segment and was approximated by a vector originating in the T10 marker (table 3.2) with a direction from the midpoint of C7 and T10 markers to the midpoint of CLAV and STRN markers (table 3.2) and a magnitude of an eighth of said vector; and
- LOWJC connects the lower back segment to the pelvis segment and was approximated by a vector originating in the midpoint of the PSI markers (table 3.2) with a direction from the midpoint of the PSI markers to the midpoint of ASI markers (table 3.2) and a magnitude of a fifth of said vector.
The estimated vector lengths used in the above estimations were chosen based on close examination of the marker positions and their distances and positions compared to anatomical data using a scaled representation of the human skeleton.

Figure 4.9 gives a graphical representation of the kinetic hierarchy of the Fighter model. Kinetic data, such as the joint moments, can only be calculated either when the subject has one foot or neither foot on the floor as calculations need be done starting from free segments and work backwards to the non-free segment. As no force plate input could be used, all the calculations are done based on inverse dynamics using segmental inertia and kinematic data. When one foot was on the floor this foot was chosen as the root segment. During the airborne phase of kicks, in theory, either foot could be used as a root as there are no resultant forces acting outside of the body. However, as errors occurred due to the differences in masses of the moving segments, high accelerations could occur which lead to inconsistent results (Personal communication with VICON technical support, 2006). Therefore the non-kicking foot, which is likely to show lower accelerations, was chosen as the root when the subject was airborne. For the purpose of the model, airborne was defined as when the vertical position of the ankle was greater than twice the value in the static trial. The duration in which only one foot was on the floor for punches was very brief and inconsistent between trials. Hence, moment data for punches were not fit for analysis (§4.5.6, §4.5.7). Two hierarchies were used to calculate joint moments as described by table 4.4. Moments at the ankle are not reported as they are expected to be insignificant (Roberts et al., 2004) but they are included in the kinetic chain (fig. 4.9).

Table 4.4: Segments used for joint moment calculation for both versions of the kinetic hierarchy

<table>
<thead>
<tr>
<th>Joint</th>
<th>Right Foot Root</th>
<th>Left Foot Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOPJC (neck)</td>
<td>Head &amp; Neck</td>
<td>Head &amp; Neck</td>
</tr>
<tr>
<td>MIDJC</td>
<td>Upper back</td>
<td>Upper back</td>
</tr>
<tr>
<td>LOWJC</td>
<td>Lower back</td>
<td>Lower back</td>
</tr>
<tr>
<td>Left Elbow</td>
<td>Left Forearm</td>
<td>Left Forearm</td>
</tr>
<tr>
<td>Left Shoulder</td>
<td>Left Humerus</td>
<td>Left Humerus</td>
</tr>
<tr>
<td>Right Elbow</td>
<td>Right Forearm</td>
<td>Right Forearm</td>
</tr>
<tr>
<td>Right Shoulder</td>
<td>Right Humerus</td>
<td>Right Humerus</td>
</tr>
<tr>
<td>Left Hip</td>
<td>Left Femur</td>
<td>Pelvis</td>
</tr>
<tr>
<td>Left Knee</td>
<td>Left Tibia</td>
<td>Left Femur</td>
</tr>
<tr>
<td>Right Hip</td>
<td>Pelvis</td>
<td>Right Femur</td>
</tr>
<tr>
<td>Right Knee</td>
<td>Right Femur</td>
<td>Right Tibia</td>
</tr>
</tbody>
</table>
4.4.5. Fighter model inertia definition

Segment definitions of the Fighter model were extended with mass and inertial properties in order to conduct kinetic calculations. The amount of segments representing central sections of the inertial model of Yeadon (1990) was altered to conform to those in the Fighter model. Similarly the direction of the longitudinal axis and the origins of these segments were different and hence some coordinate conversions were required based partly on the anthropometric measurements and partly on marker positions.

In the Fighter model the origins of the pelvis and lower back segments are located at the midpoint of a vector from the midpoint of the LPSI and RPSI markers to the midpoint of the LASI and RASI markers (table 3.2). It was assumed that Yeadon’s umbilicus measurement coincides with this point.

For the head in the Fighter model, the origin of the head-and-neck segment was at the centre of four head markers and this was assumed to be halfway between the top of the
head and the ear measurements in Yeadon’s model (1990). Hence, the centre of mass (CoM) location for the head-and-neck segment was obtained as follows (fig. 4.10):

\[
F_{\text{CoM head}} = (\text{segment length} - ((\text{top-ear})/2) - Y_{\text{CoM head}})
\]

where: 
- \(F_{\text{CoM head}}\) is the CoM location required for the Fighter model;
- segment length is the segment length according to Yeadon;
- top is the top measurement according to Yeadon;
- ear is the ear measurement according to Yeadon; and
- \(Y_{\text{CoM head}}\) is the CoM location according to Yeadon.

For the upper back, it was assumed that the origin of the Fighter model segment lay at the level of the shoulder measurement in Yeadon’s model (1990) (fig. 4.11). Hence, the CoM location for the upper back segment was obtained as follows:

\[
F_{\text{CoM upper back}} = (\text{segment length} - (\text{neck} - \text{shoulder}) - Y_{\text{CoM chest}})
\]

where: 
- \(F_{\text{CoM upper back}}\) is the CoM location required for the Fighter model;
- segment length is the segment length according to Yeadon;
- neck is the neck measurement according to Yeadon;
- shoulder is the shoulder measurement according to Yeadon; and
- \(Y_{\text{CoM head}}\) is the CoM location according to Yeadon.
Individual subject segmental inertia data was logged in parameter files, an example of which is given in Appendix 3, §A3.2. For the moments of inertia (MoI) vector, the first element refers to the x axis (frontal), the second to the y axis (transverse) and the third to the z axis (longitudinal).

The Fighter model does not include wobbling masses. Soft tissue movement has been shown to affect the kinetics and energy dissipation during impacts (Aerts et al, 1995; Gruber et al, 1998; Pain & Challis, 2001, 2002; Yue & Mester, 2002). Hence the results of the model are interpreted given this proviso.

4.4.6. Fighter model joint moment definitions

Based on the extended segment definition and the kinetic hierarchy stipulated in the model, the software used in this study ' [...] solves the equations of motion of a segment, taking into account all reactions applied to it by its child-segments in the hierarchy, as well as segment mass distribution, its motion, and gravity. The result of the function is the reaction applied to the segment, at its attachment to its parent, which achieves dynamic equilibrium' (Oxford Metrics Ltd, 2002a).

The moment definitions are dependent on the segment axes definitions. A moment at a joint is determined by calculating the reaction of the child segment in front of it in the kinetic chain, e.g. away from the root, and would be given in local coordinates of this segment (fig. 4.9; table 4.4). Moment definitions followed those of the angles: flexor, abductor or valgus, and internal rotator moments were positive; extensor, adductor or varus, and internal rotator moments were negative. For the central segments, when viewed from the front, an anticlockwise moment, i.e. trying to tilt the body to the right, was
positive. When viewed from the top a clockwise moment was positive. The *Fighter* model gives joint moments as internal moments as this is conventional (Whittle, 1990).

The axes of a kinetic child segment may not be representative of the joint axes and hence moments may be difficult to interpret. When the right foot is root, moments at the left knee are calculated based on the reaction function of the left tibia. The segment definition of the tibia uses information of the lateral ankle marker, not the lateral knee marker which is used for the femur. A similar situation occurs at the elbows. In the angle definitions, this is not an issue as the y axis of the parent segment, which approximates the flexion-extension axis, is used. Hence, new coordinate systems were created for the moments at the knees and elbows based on the method proposed by Grood and Suntay (1983). In this method a knee coordinate system is defined using the y axis of the femur as the flexion axis and the z axis of the tibia as the longitudinal axis. The x axis is obtained as the cross product of y and z axis and represents the valgus-varus axis.

Implementing these axes in BodyLanguage (Oxford Metrics Ltd., 2002a) presented a slight issue, due to the syntax of segment definitions. A segment is constructed by defining the first axis and a secondary defining line, not by defining two axes directly (Appendix 2, §A2.1). The second axis, which according to the method by Grood and Suntay (1983) must be defined, cannot be entered directly. Hence, two options that approximate Grood and Suntay’s method (1983) are available: choose the z axis of the child as the first axis and the y axis of the parent as the second defining line, or *vice versa*. For both the knee and elbow, the first scenario was the more appropriate solution as moments about the z axis were minimal for flexion-extension of the joint as no or very minimal moments are expected during these movements (fig. 4.12).
Figure 4.12: Knee moments in coordinate systems according to Grood & Suntay (1983). A. Scenario 1 z axis of tibia used as first axis; B. Scenario 2 y axis of femur used as first axis demonstrating larger moments about the z axis.
4.4.7. **Functional joint centre determination and implementation**

The functional method of Gamage and Lasenby (2002) was used to estimate JC locations *in vivo*. This method requires a minimum of three child markers, the positions of which must be expressed in a parent coordinate system constructed using three parent markers. Thus for each joint, six markers are required to implement this method.

In the subject set-up trials slow isolated movements about the individual joints (§3.5) were performed. The filtered marker position data from these trials were initially transformed from global coordinates to local parent coordinates.

The procedure to calculate and recall the functionally determined JC for use in VICON is described in Roosen and Pain (2006a). A marker position \( m \) can be expressed in local coordinates by multiplying the vector from the local origin to the marker, expressed in global coordinates, by the transpose of the rotation matrix from the local to global coordinate system (fig. 4.13):

\[
\begin{align*}
m_{\text{local}} &= \text{transpose rotation matrix} \ (m_{\text{global}} - \text{local origin}_{\text{global}}) \\
\end{align*}
\]  

(4.4)

![Figure 4.13: Schematic of representing child marker movement in a local parent coordinate system. A child segment defined by markers P, Q and R rotates about a parent defined by markers T, U and V at joint centre X. The child marker trajectories are represented by dashed lines. All marker coordinates are given in relation to the global origin O. The joint centre X needs to be expressed in terms of a parent coordinate system defined by T, U and V (Roosen & Pain, 2006a).](image)

A Matlab program implementing the method of Gamage and Lasenby (2002) was extended to first transform global coordinates for child marker data using eq. (4.4) to give the coordinates of the ICR expressed in terms of a parent coordinate system (Appendix 2, §A2.4). The described method hereafter is referred to as the JC routine. Table 4.5 shows which markers were used to calculate which JC's.
Table 4.5: Parent and child markers used to functionally determine local joint centre coordinates. For marker locations see table 3.2.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Parent markers</th>
<th>Child markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Shoulder</td>
<td>T10, STRN, LUM1</td>
<td>LUPA, LUPB, LELB</td>
</tr>
<tr>
<td>Right Shoulder</td>
<td>T10, STRN, LUM1</td>
<td>RUPA, RUPB, RELB</td>
</tr>
<tr>
<td>Left Elbow</td>
<td>LUPA, LUPB, LELB</td>
<td>LFRA, LWRA, LWRB</td>
</tr>
<tr>
<td>Right Elbow</td>
<td>RUPA, RUPB, RELB</td>
<td>RFRA, RWRA, RWRB</td>
</tr>
<tr>
<td>Left Hip</td>
<td>LASI, RASI, LPSI</td>
<td>LTHI, LTH2, LKNE</td>
</tr>
<tr>
<td>Right Hip</td>
<td>RASI, LASI, RPSI</td>
<td>RTHI, RTH2, RKNE</td>
</tr>
<tr>
<td>Left Knee</td>
<td>LTHI, LTH2, LKNE</td>
<td>LTIB, LANK, LHEE</td>
</tr>
<tr>
<td>Right Knee</td>
<td>RTHI, RTH2, RKNE</td>
<td>RTIB, RANK, RHEE</td>
</tr>
</tbody>
</table>

As discussed earlier, markers used for movement analysis need to be placed in positions where soft tissue movement is minimal (§2.3.1 and §2.3.2), especially during impact activities (§4.4.5). For the subject set-up trials, some of the markers were located on sites that would certainly demonstrate large movement artefacts during athletic movements. However, the subject set-up trials consisted of slow isolated movements and were not anticipated to include discernable soft tissue motion. These markers were removed for the dynamic trials (§3.4), which meant that a method is required to reconstruct JC locations that were originally expressed in coordinate systems that used these markers.

The model had to be run for the static trial first, as certain parts of the code were only processed for this trial type, the results of which were needed for modelling subsequent dynamic trials. By ensuring that the static trial had the full marker set, the coordinates calculated by the JC routine, could be recalled and transformed into coordinates that could be used in the dynamic trials. The following steps were required to achieve this:

1. In the static trial:
   a. Recreate all parent coordinate systems and read in the calculated JC locations from the subject parameter file;
   b. Transform the local segment coordinates into global coordinates;
   c. Transform these global coordinates into coordinates of a temporary segment that can be constructed using only markers of the dynamic marker set.

2. In the dynamic trials:
   a. Read in the temporary segment coordinates from the subject parameter file;
   b. Transform these coordinates into global coordinates;
   c. Redefine segments based on the global JC coordinates in each time-frame.
The method of recalling JCs or coordinates for the dynamic trial based on static trial or parameter file information will hereafter be referred to as the recollection routine.

In the Fighter model, JCs obtained using the recollection routine were anchored as follows:

- hip JC coordinates in a temporary pelvis segment;
- knee JC coordinates in temporary femur segments;
- shoulder JC coordinates in temporary shoulder segments; and
- elbow JC coordinates in temporary humerus segments.

The recollection routine can be used for any functional or predictive JC method that relies on a large number of markers (Stokdijk et al., 2000; Jessop & Pain, 2006) where markers are located where they can be easily knocked off. As it may not be practical to have all these markers present during the dynamic trials, the recollection routine can store relevant coordinates in the parameter file, and recall them as long as they can be expressed in a coordinate system which is constructed using only markers from the dynamic trial.

Certain JC locations can be estimated as the midpoint of two markers placed laterally on the joint (Inman, 1976; Churchill et al., 1998; Lloyd et al., 2000; Jessop & Pain, 2006). Data from this study have indicated that even during slow isolated movements, the distance between these markers fluctuates during the movement. This is in line with Woltring's (1991) argument that 'many of these [skin and soft tissue] artefacts are significantly correlated with the actual movement'. Figure 4.14 shows the distance between two laterally positioned markers for seven simple knee flexion-extension movements, captured at 250 Hz and filtered using a quintic spline (Woltring, 1986). The distance between the markers, which were placed on the condyles, varied between approximately 137 mm to 150 mm, indicating the JC position could move up to 13 mm during slow controlled movement.
Figure 4.14: Distance fluctuation of knee markers. Distance between two markers positioned laterally on the condyles of the knee during seven repetitions of isolated knee flexion-extension

The fluctuation during these slow knee flexion-extensions is likely to be caused by muscle and tendon moving over the bone at the site of marker attachment, particularly on the medial side. In an athletic activity this fluctuation may be enhanced, supporting the use of the recollection routine, i.e. calculating the midpoint in a static trial, logging this location based on markers that remain and recalling this location in the dynamic trials. In the current study, midpoints of knee markers were logged in terms of a temporary femur segment and midpoints of elbow markers were logged in terms of a temporary humerus segment.

This method of recalling JC coordinates minimises rather than eliminates the issues surrounding marker movement. The local vector for the JC will remain constant within the coordinate system in which it is reconstructed, yet this coordinate system will be subject to its own movement artefact. Careful selection of a local coordinate system should yield better results than calculating a dynamic midpoint in each time-frame of a trial. Further considerations on JC reconstruction have been examined towards the conclusion of this study and are included in the discussion (§7.8.1) and Appendix 4.
4.4.8. Discussion of joint centre routine

The JC routine was used to approximate the hip, knee, shoulder and elbow joints. Visual inspection of the locations of these JCs in static and subject set-up trials was used to assess their validity. It was assumed that marker trajectories formed spheres around the centre of rotation (CoR). Problems may occur if the recorded movements are planar as no information for a third coordinate will be available (Holzreiter, 1991).

For all subjects, unrealistic locations for the CoR of the knee were found, i.e. they were located outside the body. This was anticipated to some extent as circumduction of the shank was very limited, hence it is likely that the point the routine found is located somewhere on the flexion-extension axis of the knee joint.

For some subjects, plausible locations for the elbow JC were found. However, for other subjects as with the knee, often the CoR was located outside the body. This indicated that even though more 3D movement was possible at this joint, it was still insufficient.

For the shoulders good CoR locations were found for all subjects. Closer inspection revealed that these locations were slightly more central and higher up the body compared to predictive shoulder JCs based on two markers place anteriorly and posteriorly to the abduction-adduction axis. As the shoulder is made up of three joints, namely the glenohumeral, the sternoclavicular, and the articulation between the scapula and the thorax (Zatsiorsky, 1998), it is likely that marker movement of the child may have included some scapular movement, which could not be eliminated as the thorax was chosen as the parent. Although scapular elevation was to be avoided during the subject set-up trials for the shoulder a limited amount may have been included. Additionally, upon lifting the arm in front and behind, translation of the scapula over the ribcage will have been included. The ICR of the scapula is reported to be located near the medial end of the scapular spine, migrating towards the acromioclavicular joint during shoulder abduction (Bagg & Forrest, 1988). Provided that a full range of scapular movement for the individual was used in the set-up trial, the CoR that was found by the JC routine represents a virtual JC of the shoulder-scapula complex. This location may be useful if interested in effective arm length and considering a virtual segment from this location may allow the estimation of relevant moment arms, e.g. during swinging around a high bar in gymnastics. Figure 4.15 shows the JC locations obtained using the JC routine (red) and the predictive JC of the midpoints of shoulder markers (yellow).
Figure 4.15: Comparison of functional and predictive shoulder joint centre locations. Functionally determined shoulder joint centres are depicted in red and predictive shoulder joint centre locations (yellow) which were approximated by the midpoints of frontal and dorsal shoulder markers (cream) are depicted in yellow.

For the hip joints, good CoR locations were found for all subjects. These were generally located slightly lateral to the predictive hip JCs (Davis et al., 1991). Figure 4.16 shows the locations obtained using the JC routine (red) and the predictive JC (yellow). This is somewhat unsurprising as the hip’s JC remains fixed with some restraints at the terminal ranges and in healthy subjects is assumed to coincide with the geometrical centres of the femoral head and acetabulum (Zatsiorsky, 1998).

As no acceptable CoR locations were found for the elbows and knees, a CHORD function (Appendix 2, §A2.1) was used for TKD day 1 and the midpoint in conjunction with the recollection routine were used for TKD day 2 and karate. For the hips and shoulders the locations obtained through the JC routine as well as the afore-mentioned predictive locations were incorporated in the Fighter model. A detailed description of how all JC were defined is given in Appendix 2, §A2.2.
4.4.9. Fighter model validation and data output

The full script of the Fighter model is provided in Appendix 2, §A2.3. Before outputting data for further analyses, the following tests were conducted. The locations of the calculated JCs were carefully checked in all three trial types to ensure a JC location would not jump outside a segment during the martial arts combinations. The subject set-up trials were used to check the angle definitions and moment definition.

The output from the model was: certain marker coordinates; JC coordinates; joint angles; and joint moments. These were used to determine the instant of target contact and to perform a range of kinematic and kinetic analyses detailed below.

4.5 Post model processing

4.5.1. Target pad contact determination

To analyse the combinations critically it is imperative to define discrete instances in time where comparisons between modes can be made and variability can be expected to be minimised (Harris & Wolpert, 1998). The obvious choices are the instances in time when target contact occurs. Target contact is different to target impact. Target contact occurs
when the foot or fist first touches the target. Target impact happens some time after target contact, namely when force transfer from the foot or fist to the target is maximal. Determining the instant of target contact from motion data is difficult; however, establishing the instant of target impact is straightforward. This was determined by double differentiation of the top markers affixed to the target pads and thus constructing the target acceleration time history. Impacts with the target were represented by the peaks in the acceleration time history of the target marker. The contact point can be found by examining the acceleration graph of unfiltered data. The impact peak was preceded by a sharp smaller negative peak, which appeared to be the contact point. However, this peak is not always obvious and in such cases it is necessary to find the positive spike in the second derivative of the acceleration, the snap, preceding the impact point (Pain & Hibbs, 2007). This step is not ideal as movement data has been differentiated four times and noise will have been amplified considerably (Challis & Kerwin, 1996). Furthermore, undertaking all these steps for a large amount of trials is a lengthy and arduous process. A method of easily establishing the instant of contact from acceleration information was developed. For both TKD and karate, forty target impacts were chosen at random for which the time between contact and impact based on the above methods was determined. The average and standard deviation in this time difference were calculated for each subject. These values were sufficiently consistent to justify the use of a single value for the number of time-frames between contact and impact for each sport.

4.5.2. Kinematics 1 – Combination durations, distances and average speeds

Data between movement onset and subsequent target contacts of the combinations were analysed to determine whether the execution times and distances of the individual techniques and of the complete combinations changed significantly with the mode of execution. The potential gain obtained by the shorter duration of a technique, may be negated if the distance travelled drops such that the opponent can move backwards far enough to void it. In addition to the already determined contact points, the instant of movement onset was determined for each athlete by visually examining the 3D movement reconstructions. A distinguishable feature, e.g. the heel marker of the front leg being elevated, was chosen for each athlete and its point in time (t) was recorded for each trial. The durations (T) of the individual techniques and the full combinations were calculated as follows:
\[ T_1 = t_{\text{contact 1}} - t_{\text{onset}} \]  
\[ T_2 = t_{\text{contact 2}} - t_{\text{contact 1}} \]  
\[ T_3 = t_{\text{contact 3}} - t_{\text{contact 2}} \]  
\[ T_{\text{tot}} = t_{\text{contact 3}} - t_{\text{onset}} \]

At each of these instances the location vector (\( l \)) for the centre of the hip JCs was determined for TKD and karate athletes. As the karate athletes also performed punches the location vector for the centre of the functional shoulder JCs (§4.4.7 and §4.4.8) was also determined at these instances. The functional shoulder JCs were used as these locations include the scapular translation which is included when punching and hence produce a longer effective arm. The difference between the distances travelled at shoulder level and hip level was also examined. The whole-body CoM locations were not adequate for investigating the change in covered distance as an athlete may be leaning forward on the one technique and leaning back on the next, and hence the whole-body CoM location will not be representative of whether the segments relevant to the technique moved adequately. The locations were used to calculate distances (\( D \)) between events. The distances of each technique and the combinations were calculated as follows:

\[ D_1 = |l_{\text{contact 1}} - l_{\text{onset}}| \]  
\[ D_2 = |l_{\text{contact 2}} - l_{\text{contact 1}}| \]  
\[ D_3 = |l_{\text{contact 3}} - l_{\text{contact 2}}| \]  
\[ D_{\text{eff}} = |l_{\text{contact 3}} - l_{\text{onset}}| \]  
\[ D_{\text{tot}} = D_1 + D_2 + D_3 \]

Dividing each of these five distances by the relevant time duration in eqs. (4.5) yielded five average velocities corresponding to the individual techniques and the complete combination. Times, distances and average velocities for both execution modes were compared using an independent samples t-test (\( p=0.05 \)).

4.5.3. Kinematics 2 – Detriment, peak and contact velocity and stretch

The timings of individual techniques in a combination were analysed. If a technique is to create maximal deformation force, it should have reached peak velocity at impact (Pieter & Pieter, 1995). Maximal linear velocity of the end actuator, i.e. the foot or fist,
has been found to normally coincide with 70 to 80% of full extension in the direction of the target (Atha et al., 1985).

For kicks, the ankle JC velocity was assumed to represent the linear velocity of the foot. For punches, the fist velocity was taken from the marker placed on the mitt. For each technique, the peak and contact velocities were recorded together with their timings. The time difference between peak end actuator velocity and target contact was named the *detriment*. Additionally, the *stretch* at the instant of peak velocity and at target contact was recorded. The stretch was defined as follows.

\[
\text{Stretch}_{\text{leg}} = \frac{|(\text{AJC} - \text{HJC})|}{\text{leg length}} \times 100\% \quad (4.7)
\]

where AJC is the ankle JC location and HJC is the hip JC location; and

\[
\text{Stretch}_{\text{arm}} = \frac{|(\text{mitt} - \text{FSJC})|}{\text{arm length}} \times 100\% \quad (4.8)
\]

where mitt is the location of the mitt marker and FSJC is the functional shoulder JC location.

Values of peak velocity, contact velocity, detriment and stretch at peak and at contact between execution modes were compared using an independent samples t-test (p=0.05).

Two TKD athletes were invited to repeat the TKD combination and land the final kick on a heavy bag, weighing approximately 40 kg, to investigate whether the detriments, stretches and velocities changed if a target which offered more resistance was kicked. As this data collection involved fewer trials, contact points were determined directly for each individual trial from the target marker acceleration.

4.5.4. Target acquisition

For both TKD and karate athletes it is imperative to be accurate when striking the opponent to be awarded a score. Furthermore, the athlete aims to hit the target with a force determined by the rules of their sport. The spatial accuracy and delivery force of athletes may depend on the mode of execution. Spatial accuracy and impact force data in this study need to be quantified from data obtained from the target pad. Several experimenters have shown that for near maximal effort, force production variability decreases (Sherwood & Schmidt, 1980; Ulrich & Wing, 1991; Carlton & Newell, 1993; Schmidt and Lee, 1999) or increases at a decreasing rate than at lower force levels (Newell & Carlton, 1985;
Sherwood, Schmidt & Walter, 1988; Ulrich and Wing, 1991; Carlton & Newell, 1993) which means that spatial accuracy may increase. The martial arts techniques of this study require (near) maximal forces.

Spatial accuracy was determined based on the acceleration of the top target pad marker and target pad readout. Subjects aimed their techniques at two target pads which were held by a second person. These consisted of a standard focus pad fitted with a force transducer centrally beneath a black patch and readout display (fig. 4.17). The target gives readouts in arbitrary units between 0.00 and 4.00 pseudo force reading. The acceleration of the target pad and the readout give combined indications of how forcefully and accurately it was struck. For example, if the centre is not hit, the force transferred to the force transducer will be reduced hence the readout will be lower regardless of force level. Alternatively, if the centre is struck with low force, the readout will similarly be low. Hence, in assessing the spatial accuracy and force of impact from target pad data careful interpretation of the data was required as outlined below.

![Target pad fitted with force transducer and readout box. The force transducer is located under the central black patch](image)

Figure 4.17: Target pad fitted with force transducer and readout box. The force transducer is located under the central black patch

For a free hanging pad, based on Newton’s law, a linear relation between pad acceleration and force readout with zero intercept is expected, since:

\[
F = m \times a
\]  

(4.9)

A person holding the pads could resist the hit reducing the pad’s acceleration and increasing the readout. If the person moves the pad away from the approaching foot or fist, the acceleration will be relatively low and so will the readout. Hence, the relationship
between the measured pad acceleration and force readout is more complicated than eq. (4.9) and it is not possible to quantify the impact force from the readout as a result of the pad holder’s actions. However, typically, in such martial arts combinations little resistance will be offered to the approaching punch or kick and the target will be kept in place by an experienced pad holder until impact. Since all people holding the pads in this study were experienced in doing so, pad movement by the holder was ignored and eq. (4.9) was assumed to hold.

Logic suggests that for accurate hits, acceleration of the pad and force readout are linearly related. It can also be expected that on average the relationship between the acceleration and pseudo force readout will pass through the origin. Data for each subject were regressed separately as the effective mass a subject commits to a technique is different and for karate the data for punches and kicks were similarly regressed independently.

Based on the above assumptions the following relationships are true for the pad if the impulse created on the pad is symmetrical: the pad readout will be proportional to the velocity of the centre of the pad after impact; and the acceleration of the target marker will be proportional to the velocity of that marker after impact. A graphical representation of the target pad, the target marker, the sensor area and the qualifications of the areas on the target is shown in figure 4.18.

![Figure 4.18: Schematic of target pad areas together with marker affixed to the top of target pad](image)

Some simple mechanics are used to explain the spread of data around the regression lines. Consider a segment with effective mass \(M\) and velocity \(u_0\) hitting the target pad of mass \(m\). Figure 4.19 shows the mechanics related to an accurate impact viewed from the side. Correct hits will produce a data point on the predicted regression line. Assuming that the foot or fist and pad move at the same velocity just after impact, Newton’s Experimental
Law suggests that the coefficient of restitution equals zero. Using the relationship for linear momentum before and after impact, the following relationship applies:

\[
u_1 = \frac{M}{(M + m)} \nu_0
\]  

(4.10)

Figure 4.19: Central impact of the target viewed from the side – effective mass of the foot or fist M hits with velocity \(\nu_0\) and target with mass m moves with velocity \(\nu_1\).

Figure 4.20 is a view from above of the target being hit laterally to the centre. In this figure \(u_2\) is the only quantity that affects the target marker acceleration and the pad readout, i.e. it is a measure of both the acceleration of the marker and of the pad readout. The rotational component \(\omega\) does not affect the movement of the centre of the pad. This means that both the marker acceleration and the pad readout will be affected by a lateral hit in the same way, i.e. the acceleration and pad readout will be reduced by the same proportion. Hence, such a hit will produce a data point on the regression line which is of a lower value than it should have been. It will not be possible to distinguish this incorrect hit from correct hits with the limited data available.

Figure 4.20: Lateral impact of the target viewed from the top – effective mass of the foot or fist M hits with velocity \(\nu_0\) and target with mass m moves with velocity \(\nu_2\) and rotates with angular velocity \(\omega\).
Figure 4.21 demonstrates the mechanics of a high hit. After impact the centre of the pad will be moving at a velocity \( u \) and the top of the target, where the marker is located, will be moving at a velocity equal to \( u + \omega r \). Hence, the acceleration of the marker will be higher and the pad readout will be lower than for a correct hit. This will result in a data point below the force-acceleration regression line.

![Figure 4.21: High impact of the target viewed from the side - effective mass of the foot or fist \( M \) hits with velocity \( u_0 \) and target with mass \( m \) moves with velocity \( u \) and rotates with angular velocity \( \omega \). The top of the target moves with velocity \( u + \omega r \).](image)

Figure 4.22 demonstrates the mechanics of a low hit. After impact the centre of the pad will be moving at a velocity \( u \) and the top of the target will be moving at a velocity equal to \( u - \omega r \). Hence, the acceleration of the marker will be much lower and the pad readout will be lower (but not to same degree as the acceleration) than for a correct hit. This will result in a data point above the regression line.

![Figure 4.22: Low impact of the target viewed from the side - effective mass of the foot or fist \( M \) hits with velocity \( u_0 \) and target with mass \( m \) moves with velocity \( u \) and rotates with angular velocity \( \omega \). The top of the target moves with velocity \( u - \omega r \).](image)
These deductions for the relationship between hit location, pad readout, pad acceleration and data location on the pad force – acceleration line are summated in table 4.6. All entries are relative to the theoretically correct values that should have been produced by a hit in the centre of the pad.

<table>
<thead>
<tr>
<th>Hit Location</th>
<th>Pad Readout</th>
<th>Pad Acceleration</th>
<th>Relation to Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Below</td>
</tr>
<tr>
<td>Left or right</td>
<td>Low</td>
<td>Low</td>
<td>On</td>
</tr>
<tr>
<td>Centre</td>
<td>Correct</td>
<td>Correct</td>
<td>On</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
<td>Very Low</td>
<td>Above</td>
</tr>
</tbody>
</table>

Both pad acceleration and pseudo force are related to the velocity of the approaching foot or fist. Hence, detrending of the data in order to remove the effect of foot or fist velocity on both parameters was considered (Greig & Yeadon, 2000). This process would generate new pad accelerations and pseudo force readouts corresponding to some set velocity. For a given velocity one would expect a single point in the readout-acceleration graph and detrending would produce a cluster around this point. However, this cluster would demonstrate just as much variance as the original data and therefore this process was not conducted.

Based on the above discussion, the target pad data for each subject were regressed and the 95% confidence levels were calculated. Data points that fell within these confidence levels were assumed to be an accurate hit of the target, whilst recognising that these data will include both accurate and inaccurate lateral hits. For these accurate hits it is possible to determine whether the hit was hard or not. The number of accurate hits and their pseudo force readouts from normal mode were compared to those from 100% mode using an independent samples t-test (p=0.05). It is important to realise that the accuracy definition used was based on a small area of approximately 44cm² in the centre of the target. Realistically, any hit of the target was accurate for the purposes of the techniques in a competition setting.

4.5.5. Kinematics 3 – Joint angles at target contact

Intersegment angles were obtained using Euler angles. For each joint three orthogonal axes were created and where feasible either one or two of these axes approximated anatomical axes (see §4.4.3).
Two criteria were used to establish whether joint angles at target contact differed between execution modes. Firstly, the normal mode and 100% mode of execution were considered as two populations. This was done by taking the target contact angle data for all normal mode trials for a particular technique, joint and joint axis, and testing them against the same data for all 100% mode trials using an independent samples t-test (p=0.05). There are some restrictions in this analysis. Firstly, the sample sizes are quite small and hence they may not be normally distributed. A t-test may not reveal some relevant information as outliers may bias the test results. Other non-parametric tests were also considered but suffered similar defects due to the small sample sizes. Hence, the data were also visually compared by plotting the normal execution mode's average target contact angle ± one standard deviation and individual values from the 100% mode trials. Figure 4.23 gives an example of such a comparison. In this figure the x angles were significantly different (S) however the y angles were not due to the outlier near the top. The five other points are all below one standard deviation of the normal average. Where at least three quarters of the 100% mode results were outside the standard deviation range of the normal mode and the t-test had not shown a significant difference, these data were classified as kinematically different (K).

For the purposes of this study a significant difference and a kinematic difference in joint angle at target contact were given equal emphasis and considered a difference between execution modes. Angle differences between modes were recorded when either of the two versions of angles (two different bodies in the model based on different JC locations as described in §4.4.2) for a joint showed a statistical or kinematic difference. Angle differences between adjacent segments were investigated together with three extra angle changes between non-adjacent segments of the spine: the rotation of the trunk as a whole around the head & neck segment; the rotation of the trunk as a whole around the pelvis; and the rotation of the upper back around the pelvis (§4.4.2). Angle differences for central segments were expressed as the second segment rotating about the first, e.g. 'head – upper back' means observations made for angles of the upper back relative to the head.
4.5.6. Kinetics – Joint moments around target contact

In order to draw a comparison between joint moments around contact in different trials, a uniform time scale had to be calculated. Time rescalability usually applies to the sequential phasing of impulses (Schmidt et al., 1979; Meyer et al., 1982), which provide an activation pattern to muscles to produce the movement. If this sequential pattern of activations is rescalable in time, then so are the moments observed at the joint, since moments are directly related to the produced forces, which in turn are predominantly caused by the muscles. Hence, a relative time scale, based on durations between techniques was introduced. Two dimensionless movement time bases were chosen: \( MT_1 \) is the dimensionless movement time from technique 1 to technique 2; \( MT_2 \) is the dimensionless movement time from technique 2 to technique 3 and were calculated as follows:

\[
MT_1 = \frac{\text{real time} - t_{\text{contact}_1}}{t_{\text{contact}_2} - t_{\text{contact}_1}} \quad (4.11)
\]

\[
MT_2 = \frac{\text{real time} - t_{\text{contact}_2}}{t_{\text{contact}_3} - t_{\text{contact}_2}} \quad (4.12)
\]
Thus MT1 is 0 at technique 1 contact and 1 at technique 2 contact and MT2 is 0 at technique 2 contact and 1 at technique 3 contact. For TKD, technique 1 was investigated for MT1 = -0.5 to 0.5 MT1; technique 2 from MT1 = 0.5 to 1.5; and technique 3 from MT2 = 0 to 2. For karate, only technique 3, i.e. the kick, was observed from MT2 = 0.5 to 1.5 as the athletes spent less time on one foot (§4.4.4). A similar approach was suggested by Gentner (1987) as the constant proportion test in order to test invariance of relative timing of a motor program. The initial moment analysis was a qualitative assessment of the moment curves of each trial, which commented on the magnitudes of the moments and their repeatability between trials and on the temporal character of the moment histories. Generally, moments were reproducible in all trials as shown in figures 4.24 and 4.25 depicting representative curves from TKD and karate.

![Figure 4.24: Example TKD moment time histories for individual trials. A. normal mode; B. 100% mode](image)

![Figure 4.25: Example karate moment time histories for individual trials. A. normal mode; B. 100% mode](image)

All joint moments were normalised by body mass and interpolated in Matlab to give a data point every 0.01 in MT1 or MT2. For each execution mode and subject the mean moment and its standard deviation dimensionless time history was evaluated. The standard
deviation at each point in time was used as a measure of variability. These data were compared using the whole normal mode sample and the whole 100% mode sample for each technique with an independent samples t-test (p=0.05). This gave an indication of whether the technique execution as a whole was more variable in one mode than the other.

In order to test the viability of comparing standard deviation time histories from two types of trials using a t-test, three theoretical signal groups were created. In the first group a sine wave was varied by 10%, i.e. the amplitude and translation of the wave were increased and decreased by 10% resulting in a group of five (1 + 4) sine waves. The signals ran from $-2\pi$ to $2\pi$, were divided into 100 points, and the standard deviation time history was determined. Similarly, other groups of sine signals with different percentage variations were created and their standard deviation histories were obtained. It was found that comparing the standard deviation history of a group that was varied by 11.5% showed no significant difference to the standard deviation history of the 10% group (p=0.09), but if the sine waves were varied by 12% their standard deviation history was significantly different to that of the 10% group (p=0.03). These results suggest that comparing the standard deviation histories of the normal mode trials with those of the 100% mode trials can give a good indication of whether the variability of moments over the duration of a technique are statistically different. Average and standard deviation moment time history curves were constructed as shown in figure 4.26.

Figure 4.26: Example average and standard deviation moment time history curves for normal (left) and 100% mode (right).
4.5.7. **Approximate Entropy — Unfiltered joint angle histories**

The moment data calculations for the punches of karate subjects were unreliable as the subject either had both feet on the floor, or the timing of one foot landing on or leaving the floor was inconsistent (§4.4.4). The moment curves for the punches could not therefore be used for analysis and an alternative method to investigate variability in technique production was required. Joint angles were calculated from the unfiltered data and each trial was divided into individual techniques as per eq. (4.5). The approximate entropy (ApEn) for the angle data about each axis of each joint for the duration of a technique was calculated using a Matlab routine by Challis (2001) which represented the method suggested by Pincus (1991). ApEn takes values from 0 upwards where 0 denotes a completely regular signal and the higher the ApEn value the more irregular. Pincus (1991) ran tests on several data with a sample size of 300 for run length 2 and filter lengths of 1.0, 0.1, 0.5, 0.05, and 0.025. The sample size of each technique in this study was approximately 150. It was suggested that as long as the ApEn of different data sets is calculated using the same parameters, the values can be compared (Pincus, 1991). In this study a run length of 2 and filter length of 0.5 were used.

The ApEn for each joint angle in each trial and performance mode had been established. The values of ApEn in the normal mode were compared to those of the 100% with an independent samples t-test (p=0.05). For karate, moment and ApEn data were available for the kick and were compared to further investigate the variability at all joints. Based on the findings of this comparison, it was decided to also calculate the ApEn for the TKD techniques.
Chapter 5

RESULTS 1 – TAEKWONDO DATA

5.1 Chapter outline

This chapter presents the results for the TKD subjects. First, the data relevant to determining the instant in time of target contact are presented. Then, kinematic and target acquisition results are presented. The first set of kinematic results pertains to the durations, distances, and velocities of the combination as well as its individual components of both modes of execution. The second set of kinematic results pertains to the contact timing, the linear foot velocity and the stretch within each individual kick of both modes of execution. The last set of kinematic results presents joint angle differences at target contact between the two modes of execution. Next, the kinetic results, comparing moment patterns about the joints between both execution modes are presented. Lastly, the approximate entropy (ApEn) of joint angle histories for the individual techniques in both execution modes are compared. In the tables K1, K2 and K3 refer to kicks 1, 2 and 3 of the TKD combination.

5.2 TKD target pad contact determination

Table 5.1 shows the average time difference between target contact and impact (§4.5.1), corresponding to peak acceleration of the pad marker, for forty randomly selected target impacts.

Table 5.1: TKD time difference and standard deviation between the instant of target contact and impact for each subject (average ± standard deviation)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Time difference (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>TKD2</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>TKD3</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>TKD4</td>
<td>13 ± 2</td>
</tr>
<tr>
<td>TKD5</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>

As data were captured at 250Hz the above time differences are equivalent to approximately two or three time-frames ± ½ time-frame. Hence, the time of contact was
defined as three time-frames before the time of impact, i.e. 12 ms. Based on this definition, the contact point was established for all trials.

5.3 TKD kinematic and target acquisition results

5.3.1. Kinematics I - Combination durations, distances and average speeds results

Table 5.2 shows the mean execution times for both execution modes. Significant differences between modes (p ≤ 0.05) are indicated by *.

Table 5.2: TKD execution times (s) (mean ± standard deviation) for all three techniques and for the combination in both modes of execution (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset – K1 N</td>
<td>0.49 ± 0.02</td>
<td>0.54 ± 0.02</td>
<td>0.56 ± 0.03</td>
<td>0.52 ± 0.03 *</td>
<td>0.51 ± 0.02</td>
</tr>
<tr>
<td>Onset – K1 100</td>
<td>0.49 ± 0.03</td>
<td>0.54 ± 0.03</td>
<td>0.56 ± 0.05</td>
<td>0.59 ± 0.07 *</td>
<td>0.52 ± 0.02</td>
</tr>
<tr>
<td>K1 – K2 N</td>
<td>0.48 ± 0.01 *</td>
<td>0.60 ± 0.03 *</td>
<td>0.56 ± 0.05 *</td>
<td>0.59 ± 0.03 *</td>
<td>0.50 ± 0.01</td>
</tr>
<tr>
<td>K1 – K2 100</td>
<td>0.45 ± 0.02 *</td>
<td>0.53 ± 0.02 *</td>
<td>0.49 ± 0.04 *</td>
<td>0.55 ± 0.03 *</td>
<td>0.47 ± 0.03</td>
</tr>
<tr>
<td>K2 – K3 N</td>
<td>0.22 ± 0.01 *</td>
<td>0.25 ± 0.01 *</td>
<td>0.22 ± 0.01 *</td>
<td>0.21 ± 0.00 *</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td>K2 – K3 100</td>
<td>0.20 ± 0.01 *</td>
<td>0.24 ± 0.01 *</td>
<td>0.21 ± 0.01 *</td>
<td>0.20 ± 0.01 *</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td>Onset – K3 N</td>
<td>1.19 ± 0.02 *</td>
<td>1.39 ± 0.03 *</td>
<td>1.34 ± 0.06 *</td>
<td>1.33 ± 0.02</td>
<td>1.23 ± 0.02</td>
</tr>
<tr>
<td>Onset – K3 100</td>
<td>1.14 ± 0.04 *</td>
<td>1.31 ± 0.03 *</td>
<td>1.26 ± 0.06 *</td>
<td>1.33 ± 0.07</td>
<td>1.23 ± 0.05</td>
</tr>
</tbody>
</table>
The mean execution distances for the combination are shown in mm in table 5.3. Significant differences between modes (p \leq 0.05) are indicated by *

Table 5.3: TKD execution distances (mm) (mean ± standard deviation) of the three techniques and for the total and effective distances of the combination (§4.5.2) (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - K1 N</td>
<td>881 ± 8 *</td>
<td>758 ± 67 *</td>
<td>1176 ± 45</td>
<td>1019 ± 49</td>
<td>1080 ± 56 *</td>
</tr>
<tr>
<td>Onset - K1 100</td>
<td>829 ± 23 *</td>
<td>882 ± 61 *</td>
<td>1275 ± 83</td>
<td>1127 ± 191</td>
<td>1179 ± 48 *</td>
</tr>
<tr>
<td>K1 - K2 N</td>
<td>1022 ± 35 *</td>
<td>939 ± 19</td>
<td>1344 ± 86</td>
<td>1145 ± 36</td>
<td>1458 ± 70</td>
</tr>
<tr>
<td>K1 - K2 100</td>
<td>900 ± 46 *</td>
<td>946 ± 24</td>
<td>1305 ± 85</td>
<td>1114 ± 117</td>
<td>1495 ± 81</td>
</tr>
<tr>
<td>K2 - K3 N</td>
<td>443 ± 17 *</td>
<td>366 ± 10 *</td>
<td>524 ± 24</td>
<td>392 ± 18</td>
<td>539 ± 21</td>
</tr>
<tr>
<td>K2 - K3 100</td>
<td>379 ± 25 *</td>
<td>400 ± 16 *</td>
<td>530 ± 33</td>
<td>386 ± 45</td>
<td>504 ± 43</td>
</tr>
<tr>
<td>Effective N</td>
<td>2340 ± 56 *</td>
<td>2049 ± 80 *</td>
<td>3038 ± 60</td>
<td>2548 ± 57</td>
<td>2289 ± 138 *</td>
</tr>
<tr>
<td>Effective 100</td>
<td>2101 ± 58 *</td>
<td>2219 ± 30 *</td>
<td>3104 ± 132</td>
<td>2571 ± 111</td>
<td>2472 ± 119 *</td>
</tr>
<tr>
<td>Total N</td>
<td>2346 ± 56 *</td>
<td>2061 ± 81 *</td>
<td>3045 ± 59</td>
<td>2557 ± 57</td>
<td>3077 ± 96</td>
</tr>
<tr>
<td>Total 100</td>
<td>2108 ± 58 *</td>
<td>2228 ± 27 *</td>
<td>3110 ± 133</td>
<td>2627 ± 112</td>
<td>3178 ± 121</td>
</tr>
</tbody>
</table>

Using the data from tables 5.2 and 5.3, the average movement speeds for each section of the combination were calculated and are given in table 5.4. Significant differences between modes (p \leq 0.05) are indicated by *

Table 5.4: TKD combination execution speeds (m/s) for the three techniques and combination (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - K1 N</td>
<td>1.80 ± 0.06</td>
<td>1.42 ± 0.14 *</td>
<td>2.10 ± 0.14</td>
<td>1.95 ± 0.14</td>
<td>2.11 ± 0.14</td>
</tr>
<tr>
<td>Onset - K1 100</td>
<td>1.69 ± 0.12</td>
<td>1.63 ± 0.14 *</td>
<td>2.29 ± 0.26</td>
<td>1.93 ± 0.34</td>
<td>2.28 ± 0.14</td>
</tr>
<tr>
<td>K1 - K2 N</td>
<td>2.12 ± 0.09 *</td>
<td>1.56 ± 0.07 *</td>
<td>2.40 ± 0.25 *</td>
<td>1.93 ± 0.12</td>
<td>3.06 ± 0.16</td>
</tr>
<tr>
<td>K1 - K2 100</td>
<td>1.99 ± 0.13 *</td>
<td>1.78 ± 0.08 *</td>
<td>2.65 ± 0.26 *</td>
<td>2.03 ± 0.24</td>
<td>3.15 ± 0.26</td>
</tr>
<tr>
<td>K2 - K3 N</td>
<td>2.01 ± 0.09</td>
<td>1.44 ± 0.06 *</td>
<td>2.36 ± 0.14 *</td>
<td>1.86 ± 0.09</td>
<td>2.25 ± 0.11</td>
</tr>
<tr>
<td>K2 - K3 100</td>
<td>1.91 ± 0.14</td>
<td>1.67 ± 0.08 *</td>
<td>2.57 ± 0.17 *</td>
<td>1.98 ± 0.23</td>
<td>2.11 ± 0.20</td>
</tr>
<tr>
<td>Effective N</td>
<td>1.96 ± 0.06 *</td>
<td>1.47 ± 0.07 *</td>
<td>2.26 ± 0.11 *</td>
<td>1.92 ± 0.05</td>
<td>1.86 ± 0.12</td>
</tr>
<tr>
<td>Effective 100</td>
<td>1.84 ± 0.06 *</td>
<td>1.69 ± 0.04 *</td>
<td>2.47 ± 0.16 *</td>
<td>1.93 ± 0.13</td>
<td>2.01 ± 0.13</td>
</tr>
<tr>
<td>Total N</td>
<td>1.97 ± 0.06 *</td>
<td>1.48 ± 0.07 *</td>
<td>2.27 ± 0.11 *</td>
<td>1.93 ± 0.05</td>
<td>2.51 ± 0.09</td>
</tr>
<tr>
<td>Total 100</td>
<td>1.84 ± 0.08 *</td>
<td>1.70 ± 0.04 *</td>
<td>2.47 ± 0.17 *</td>
<td>1.98 ± 0.13</td>
<td>2.58 ± 0.15</td>
</tr>
</tbody>
</table>
5.3.2. *Kinematics 2 – Detriment, peak and contact velocity and stretch results*

Table 5.5 shows the mean detriments, foot velocities and stretches for the three kicks for the normal mode and 100% execution modes (§4.5.3). Significant differences (p ≤ 0.05) are indicated by *.
Table 5.5: TKD detriment, peak velocity and contact velocity and stretch data (mean ± standard deviation) for the three kicks of the combination (N = normal mode; 100 = 100% mode; * is significantly different between modes; italics indicate that contact occurred before peak foot velocity was reached)

<table>
<thead>
<tr>
<th>Subj.</th>
<th>Mode</th>
<th>Detriment (ms)</th>
<th>Peak Velocity (m/s)</th>
<th>Contact Velocity (m/s)</th>
<th>Detriment (ms)</th>
<th>Peak Velocity (m/s)</th>
<th>Contact Velocity (m/s)</th>
<th>Detriment (ms)</th>
<th>Peak Velocity (m/s)</th>
<th>Contact Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>N</td>
<td>-2 ± 2</td>
<td>11.0 ± 0.3</td>
<td>11.0 ± 0.3</td>
<td>10 ± 4 *</td>
<td>12.9 ± 0.4</td>
<td>12.3 ± 0.4</td>
<td>2 ± 4</td>
<td>12.3 ± 0.3</td>
<td>12.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>-1 ± 6</td>
<td>11.3 ± 0.3</td>
<td>11.2 ± 0.3</td>
<td>17 ± 3 *</td>
<td>12.8 ± 0.4</td>
<td>11.4 ± 0.6</td>
<td>2 ± 3</td>
<td>12.8 ± 0.5</td>
<td>12.7 ± 0.4</td>
</tr>
<tr>
<td>TKD2</td>
<td>N</td>
<td>12 ± 4</td>
<td>8.50 ± 0.31</td>
<td>8.09 ± 0.38</td>
<td>2 ± 4</td>
<td>11.0 ± 0.3</td>
<td>11.0 ± 0.3</td>
<td>11 ± 7 *</td>
<td>10.2 ± 0.2</td>
<td>10.1 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>13 ± 7</td>
<td>8.85 ± 0.15</td>
<td>8.45 ± 0.11</td>
<td>2 ± 4</td>
<td>11.6 ± 0.4</td>
<td>11.6 ± 0.3</td>
<td>2 ± 2 *</td>
<td>11.0 ± 0.4</td>
<td>11.0 ± 0.3</td>
</tr>
<tr>
<td>TKD3</td>
<td>N</td>
<td>2 ± 4</td>
<td>13.1 ± 0.4</td>
<td>13.0 ± 0.3</td>
<td>13 ± 3</td>
<td>14.0 ± 0.7</td>
<td>12.5 ± 0.6</td>
<td>7 ± 2</td>
<td>13.4 ± 0.5</td>
<td>13.1 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>3 ± 3</td>
<td>13.4 ± 0.3</td>
<td>13.2 ± 0.3</td>
<td>17 ± 8</td>
<td>14.0 ± 0.5</td>
<td>11.9 ± 0.3</td>
<td>13 ± 9</td>
<td>13.1 ± 0.8</td>
<td>12.6 ± 0.7</td>
</tr>
<tr>
<td>TKD4</td>
<td>N</td>
<td>12 ± 6</td>
<td>12.4 ± 0.1</td>
<td>11.1 ± 0.3</td>
<td>15 ± 5</td>
<td>13.0 ± 0.4</td>
<td>11.6 ± 0.8</td>
<td>11 ± 4</td>
<td>12.5 ± 0.3</td>
<td>11.7 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>12 ± 5</td>
<td>12.4 ± 0.5</td>
<td>11.3 ± 0.1</td>
<td>20 ± 6</td>
<td>12.5 ± 0.4</td>
<td>10.4 ± 0.2</td>
<td>10 ± 7</td>
<td>12.4 ± 0.4</td>
<td>11.8 ± 0.9</td>
</tr>
<tr>
<td>TKD5</td>
<td>N</td>
<td>19 ± 5</td>
<td>11.4 ± 0.3</td>
<td>8.71 ± 0.3</td>
<td>17 ± 5</td>
<td>12.5 ± 0.6</td>
<td>10.3 ± 1.6</td>
<td>10 ± 10</td>
<td>10.9 ± 0.3</td>
<td>9.66 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>15 ± 5</td>
<td>11.6 ± 0.3</td>
<td>9.75 ± 0.3</td>
<td>21 ± 5</td>
<td>12.8 ± 0.5</td>
<td>9.00 ± 1.5</td>
<td>10 ± 6</td>
<td>11.0 ± 0.3</td>
<td>9.93 ± 0.4</td>
</tr>
</tbody>
</table>

Note: detriment is time difference between peak foot velocity and target contact; %stretch = | (AJC – HJC) | / leg length x 100% (§4.5.3)
To examine the group average data, the detriments, velocities and stretches were normalised and averaged. Detriments were normalised by dividing them by the execution time of the technique; and velocities and stretches were normalised by dividing the values per subject by the highest value obtained for that subject for that particular kick. Table 5.6 below shows a summary of the data for all subjects once normalised (Roosen & Pain, 2006b).

Table 5.6: TKD averaged normalised detriments, velocities and stretches, and average component timings for all subjects and both execution modes

<table>
<thead>
<tr>
<th></th>
<th>K1 normal</th>
<th>K1 100%</th>
<th>K2 normal</th>
<th>K2 100%</th>
<th>K3 normal</th>
<th>K3 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalised detriment (%)</td>
<td>1.58</td>
<td>1.60</td>
<td>2.11</td>
<td>3.29</td>
<td>3.67</td>
<td>3.55</td>
</tr>
<tr>
<td>actual detriment (s)</td>
<td>0.008</td>
<td>0.009</td>
<td>0.012</td>
<td>0.017</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>component skill duration (s)</td>
<td>0.524</td>
<td>0.544</td>
<td>0.546</td>
<td>0.505</td>
<td>0.230</td>
<td>0.212</td>
</tr>
<tr>
<td>normalised peak velocity (%)</td>
<td>94.1</td>
<td>96.1</td>
<td>94.5</td>
<td>94.5</td>
<td>93.3</td>
<td>92.3</td>
</tr>
<tr>
<td>normalised contact velocity (%)</td>
<td>88.9</td>
<td>92.0</td>
<td>90.1</td>
<td>84.1</td>
<td>86.5</td>
<td>92.7</td>
</tr>
<tr>
<td>stretch at contact (%)</td>
<td>85.0</td>
<td>85.3</td>
<td>89.8</td>
<td>93.4</td>
<td>82.4</td>
<td>82.5</td>
</tr>
</tbody>
</table>

The results for repeating the combination on the heavy bag indicated that the kicks were executed quite differently to the original data collection (table 5.7). On contact with the bag, the foot was still accelerating (negative detriment) on average, peak and contact velocities were higher, and the stretch was much lower than the previous results for kick 3 (table 5.5).

Table 5.7: Detriment, contact velocity and peak velocity and stretch data (mean ± standard deviation) trials executed on the heavy bag by two TKD subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Detriment (ms)</th>
<th>Contact</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity (m/s)</td>
<td>%Stretch</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>TKD1</td>
<td>-1 ± 3</td>
<td>15.8 ± 0.4</td>
<td>73.2 ± 2.1</td>
</tr>
<tr>
<td>TKD3</td>
<td>-4 ± 6</td>
<td>14.6 ± 0.6</td>
<td>76.9 ± 2.3</td>
</tr>
</tbody>
</table>

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5.3.3. Target acquisition results

Table 5.8 shows the results of the regressions for target pad readout and top target marker acceleration for the TKD subjects (§4.5.4). From these data, the hits for kick 2 and kick 3 could be qualified as being accurate or not accurate, where 'accurate' was defined as lying within the 95% confidence level of the regression line. Table 5.9 shows the percentage of kicks that fell within, below, or above the 95% confidence levels of each subject's regression.

Table 5.8: Regression of target pad readout against target pad marker acceleration for TKD subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>R Square</th>
<th>Standard Error</th>
<th>Significance</th>
<th>Coefficient</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>0.75</td>
<td>0.760</td>
<td>1.45E-07</td>
<td>0.00145</td>
<td>0.00107</td>
<td>0.00184</td>
</tr>
<tr>
<td>TKD2</td>
<td>0.83</td>
<td>0.567</td>
<td>9.94E-10</td>
<td>0.00115</td>
<td>0.00092</td>
<td>0.00138</td>
</tr>
<tr>
<td>TKD3</td>
<td>0.88</td>
<td>0.575</td>
<td>1.51E-08</td>
<td>0.00107</td>
<td>0.00086</td>
<td>0.00128</td>
</tr>
<tr>
<td>TKD4</td>
<td>0.89</td>
<td>0.637</td>
<td>8.06E-08</td>
<td>0.00207</td>
<td>0.00166</td>
<td>0.00249</td>
</tr>
<tr>
<td>TKD5</td>
<td>0.95</td>
<td>0.392</td>
<td>1.11E-13</td>
<td>0.00159</td>
<td>0.00142</td>
<td>0.00177</td>
</tr>
</tbody>
</table>

Table 5.9: Percentage of TKD kicks within, below and above the 95% confidence level of the subject specific regressions between pad readout and pad marker acceleration for normal and 100% mode of execution for kick 2 and kick 3 (no data for kick 1 is available as these kicks were aimed at the same pad as kick 3)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Kick</th>
<th>Mode</th>
<th>Total number of kicks</th>
<th>% within</th>
<th>% below</th>
<th>% above</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>2</td>
<td>Normal</td>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>6</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Normal</td>
<td>5</td>
<td>20.0</td>
<td>0.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>6</td>
<td>50.0</td>
<td>16.7</td>
<td>33.3</td>
</tr>
<tr>
<td>TKD2</td>
<td>2</td>
<td>Normal</td>
<td>6</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>5</td>
<td>60.0</td>
<td>0.0</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Normal</td>
<td>6</td>
<td>50.0</td>
<td>16.7</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>6</td>
<td>33.3</td>
<td>16.7</td>
<td>50.0</td>
</tr>
<tr>
<td>TKD3</td>
<td>2</td>
<td>Normal</td>
<td>5</td>
<td>20.0</td>
<td>0.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Normal</td>
<td>4</td>
<td>75.0</td>
<td>0.0</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>4</td>
<td>25.0</td>
<td>0.0</td>
<td>25.0</td>
</tr>
<tr>
<td>TKD4</td>
<td>2</td>
<td>Normal</td>
<td>5</td>
<td>20.0</td>
<td>0.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>20.0</td>
<td>0.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Normal</td>
<td>5</td>
<td>80.0</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>80.0</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td>TKD5</td>
<td>2</td>
<td>Normal</td>
<td>5</td>
<td>20.0</td>
<td>0.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>6</td>
<td>33.3</td>
<td>50.0</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Normal</td>
<td>5</td>
<td>40.0</td>
<td>60.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>5</td>
<td>80.0</td>
<td>0.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

It is important to examine whether the impact force of these accurate hits in 100% mode differed from that in normal mode. Table 5.10 shows the average pad readouts and standard deviations for data points within the 95% confidence level of the regression line for separate kicks. As discussed earlier (§4.5.4), these data points are likely to also include incorrect hits that happened laterally.
### Table 5.10: Target pad readout for accurate kicks (mean ± standard deviation)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Kick</th>
<th>Normal mode pad readout</th>
<th>100% mode pad readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>2</td>
<td>-</td>
<td>1.75 ± 0.42</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.35</td>
<td>-</td>
</tr>
<tr>
<td>TKD2</td>
<td>2</td>
<td>-</td>
<td>0.93 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.55 ± 0.36</td>
<td>1.78 ± 0.04</td>
</tr>
<tr>
<td>TKD3</td>
<td>2</td>
<td>0.95</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.01 ± 0.30</td>
<td>1.35</td>
</tr>
<tr>
<td>TKD4</td>
<td>2</td>
<td>1.5</td>
<td>1.15 ± 0.60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.85</td>
<td>2.20 ± 0.45</td>
</tr>
<tr>
<td>TKD5</td>
<td>2</td>
<td>0.72</td>
<td>1.02 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.29 ± 0.20</td>
<td>1.68 ± 0.47</td>
</tr>
</tbody>
</table>

### Table 5.11: Target pad readout for accurate kicks averaged over kick 2 and kick 3 (mean ± standard deviation)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Normal mode pad readout</th>
<th>100% mode pad readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD1</td>
<td>1.35</td>
<td>1.75 ± 0.42</td>
</tr>
<tr>
<td>TKD2</td>
<td>1.55 ± 0.36</td>
<td>1.27 ± 0.47</td>
</tr>
<tr>
<td>TKD3</td>
<td>1.75 ± 0.58</td>
<td>1.35</td>
</tr>
<tr>
<td>TKD4</td>
<td>1.68 ± 0.23</td>
<td>1.85 ± 0.70</td>
</tr>
<tr>
<td>TKD5</td>
<td>1.77 ± 0.92</td>
<td>1.46 ± 0.50</td>
</tr>
</tbody>
</table>

### 5.3.4. Kinematics 3 – Joint angle at target contact comparison results

Tables 5.12 to 5.14 give the significant (S) or kinematic (K) differences observed when comparing joint angles at target contact between normal and 100% modes of execution (§4.5.5). The first entry pertains to the y axis, the second to the x axis and the third to the z axis (§4.4.3; Appendix 2 for axes definitions).

Angles for the kicking leg are followed by angles for the non-kicking leg and finally by angles for the central segments. It is important to realise, especially for central segments that these are relative angle differences of the latter segment rotating about the former. The total number of statistically or kinematically significant angle differences is also shown for each subject. This total included information from greyed areas of the table which pertain to non-adjacent central segment angle differences (§4.5.5).
Table 5.12: Significant (S) and kinematic (K) angle differences in 100% mode compared to normal mode for TKD kick 1 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- S Abduction</td>
<td>↑ K Flexion</td>
<td>↓ K Flexion</td>
<td>↑ K Flexion</td>
<td>↑ S Flexion</td>
<td>-</td>
</tr>
<tr>
<td>↓ S Abduction</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K range of flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Extension</td>
<td>↓ K Extension</td>
<td>↓ K Extension</td>
<td>↓ K Extension</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ K Abduction</td>
<td>↑ K Abduction</td>
<td>↑ S Extension</td>
<td>↑ K Extension</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↓ S External Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- K Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Head-Trunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- K CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Backward Extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Head – Upper Back</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- S Backward Extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Upper back – Lower back</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ K Forward Flexion</td>
<td>-</td>
</tr>
<tr>
<td>- S Forward Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Lower back – Pelvis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- K CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Upper back – Pelvis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ K Forward Flexion</td>
<td>-</td>
</tr>
<tr>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>↓ S Left Flexion</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- K CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pelvis-Trunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ K Forward Flexion</td>
<td>-</td>
</tr>
<tr>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S Left Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- S CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Differences</strong></td>
<td><strong>18</strong></td>
<td><strong>17</strong></td>
<td><strong>15</strong></td>
<td><strong>16</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
</table>
Table 5.13: Significant (S) and kinematic (K) angle differences in 100% mode compared to normal mode for TKD kick 2 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Abduction</td>
<td>↓ K Abduction</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ K Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K range of flexion</td>
<td>K range of flexion</td>
<td>K range of flexion</td>
<td>K range of flexion</td>
<td>↑ K Flexion</td>
</tr>
<tr>
<td>↓ S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↑ S Extension</td>
</tr>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Extension</td>
<td>↑ K Internal Rotation</td>
<td>↑ S Extension</td>
<td>↑ K Extension</td>
<td>↑ K Extension</td>
</tr>
<tr>
<td>↑ S Abduction</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ K External Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Extension</td>
<td>↑ K Extension</td>
<td>↑ S Extension</td>
<td>↑ K Extension</td>
<td>↑ K Extension</td>
</tr>
<tr>
<td>-</td>
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</tr>
<tr>
<td><strong>Head-Trunk</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>↓ S aCW Rotation</td>
<td>↑ K Left Flexion</td>
<td>-</td>
<td>-</td>
<td>↑ K Forward Flexion</td>
</tr>
<tr>
<td>↑ K range aCW rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Head - Upper Back</strong></td>
<td></td>
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</tr>
<tr>
<td>↑ S Left Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↑ S Forward Flexion</td>
</tr>
<tr>
<td>↓ S aCW → CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↑ K Left Flexion</td>
</tr>
<tr>
<td><strong>Upper back - Lower back</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>↑ S Forward Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ K aCW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Lower back - Pelvis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Left Flexion</td>
<td>↑ K Left Flexion</td>
<td>↑ K Backward Extension</td>
<td>↑ K Backward Extension</td>
<td>K range of flexion</td>
</tr>
<tr>
<td>↑ S aCW Rotation</td>
<td>↑ K aCW Rotation</td>
<td>↑ S aCW Rotation</td>
<td>↑ S aCW Rotation</td>
<td>↑ K Left Flexion</td>
</tr>
<tr>
<td><strong>Upper back - Pelvis</strong></td>
<td></td>
<td></td>
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<tr>
<td>-</td>
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</tr>
<tr>
<td><strong>Pelvis-Trunk</strong></td>
<td></td>
<td></td>
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<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ K CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Differences</strong></td>
<td>13</td>
<td>10</td>
<td>7</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 5.14: Significant (S) and kinematic (K) angle differences in 100% mode compared to normal mode for TKD kick 3 († increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ K Abduction</td>
<td>-</td>
<td>-</td>
<td>↑ S Flexion</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K range of flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↑ K Flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Extension</td>
<td>↓ K Extension</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ K Flexion</td>
<td>↓ K Abduction</td>
<td>↓ K External Rotation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ K External Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ K Flexion</td>
<td>↓ K Flexion</td>
<td>↓ S Varus Rotation</td>
<td>K range of flexion</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Ankle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Valgus Rotation</td>
<td>↑ S External Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Head-Trunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ K Forward Flexion</td>
<td>↑ K Forward Flexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>↑ S Left Flexion</td>
<td>↑ K Left Flexion</td>
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<td></td>
</tr>
<tr>
<td><strong>Head – Upper Back</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Left Flexion</td>
<td>↑ K Left Flexion</td>
<td>-</td>
<td>-</td>
<td>↑ K Forward Flexion</td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Upper Back – Lower back</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>↑ K Forward Flexion</td>
<td>-</td>
<td>-</td>
<td>↑ K CW Rotation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower back – Pelvis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Left Flexion</td>
<td>-</td>
<td>-</td>
<td>K range of flexion</td>
<td>-</td>
</tr>
<tr>
<td>↓ S CW Rotation</td>
<td>↓ S CW Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Upper back–Pelvis</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pelvis-Trunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ K Left Flexion</td>
<td>↑ K Left Flexion</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Differences</strong></td>
<td>19</td>
<td>8</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>
The tables above highlight a number of differences between execution modes in joints angles at target contact for the three kicks. To put these tables into context the maximum standard deviations for the joint angles in normal mode from all three contacts are given in table 5.15. As defined in §4.5.5, kinematic difference means that about three quarters of the 100% mode results lie outside ± one standard deviation from the average of the normal mode kinematics.

Table 5.15: TKD maximal standard deviations of contact joint angles for normal mode (for axis definitions see §4.4.3)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Y (deg.)</th>
<th>X (deg.)</th>
<th>Z (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>9.9</td>
<td>6.6</td>
<td>25.7</td>
</tr>
<tr>
<td>Knee</td>
<td>20.0</td>
<td>10.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Ankle</td>
<td>16.3</td>
<td>5.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Head – trunk</td>
<td>6.3</td>
<td>6.8</td>
<td>10.9</td>
</tr>
<tr>
<td>Head – upper back</td>
<td>7.3</td>
<td>5.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Upper back – lower back</td>
<td>4.7</td>
<td>4.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Lower back – pelvis</td>
<td>5.4</td>
<td>2.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Upper back – pelvis</td>
<td>7.0</td>
<td>6.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Pelvis – trunk</td>
<td>6.9</td>
<td>5.5</td>
<td>6.6</td>
</tr>
</tbody>
</table>

A description of the most commonly observed angle differences (i.e. at least three differences per joint axis) is given below. It is assumed that the athlete aimed to keep their head pointed towards the target in the description of longitudinal rotations of the back. Differences for individual joints are summarised below if at least three out of five subjects demonstrated a difference for that joint angle.

Kick 1

When looking at all subjects together, kick 1 (fig. 5.1) showed the largest number of angle differences (table 5.12). Presumably, this was mainly due to it being the first move of the combination and the TKD athlete needed to get their body moving. For all three kicks, most differences between normal and 100% modes occurred in the trunk segments. Kick 1 was the only kick off the front leg. Differences for individual joints are summarised below if at least three out of five subjects demonstrated a difference for that joint angle.
Kicking Hip: increased flexion 3/5 (3 subjects out of 5)
decreased abduction 3/5

Kicking Ankle: decreased extension 3/5

Head – trunk: decreased CW rotation 5/5

Head – Upper back: increased backward extension 3/5
decreased CW rotation 3/5

Upper back – lower back: increased forward flexion 3/5

Lower back – pelvis: increased forward flexion 3/5
decreased CW rotation 2/5; increased CW rotation 1/5; range of CW rotation 1/5

Upper back – pelvis: increased forward flexion 4/5
decreased left flexion 2/5; increased left flexion 1/5

Pelvis – trunk: increased forward flexion 5/5
decreased aCW rotation 3/5
Kick 2

Fewer differences between execution modes were observed in the kicking and the supporting leg during kick 2 (table 5.13). Although a number of changes were observed in the trunk segments, it was less than in kick 1. The main technical differences in execution of kick 2 (fig. 5.2) when comparing it to kick 1 are:

1. it is done with the back foot (in this case the right foot); and
2. the kick travels almost purely in the sagittal plane rather than between the transverse and sagittal plane.

![Figure 5.2: Kick 2 contact](image)

Kicking Knee: decreased flexion 1/5; range of flexion 4/5

Non-kicking Ankle: increased extension 5/5

Head – trunk: decreased aCW rotation 2/5; range aCW rotation 2/5

Head – upper back: increased CW rotation 3/5

Upper back – lower back: increased aCW rotation 2/5; decreased aCW rotation 1/5

Lower back – pelvis: increased backward extension 2/5; range of flexion 1/5 increased left flexion 4/5 increased aCW rotation 4/5; decreased aCW rotation 1/5

Pelvis – trunk: increased CW rotation 3/5
Kick 3

Similarly to kick 1, kick 3 was executed with the left leg (fig. 5.3) and had already been initiated as kick 2 hit the target. The main differences in its execution compared to kick 1 are:

1. it is done with the back leg; and
2. it has an aerial phase which should allow the kick to hit the target before the non-kicking leg lands.

![Figure 5.3: Kick 3 contact](image)

- **Kicking Knee:** increased flexion 1/5; range of flexion 2/5
- **Non-kicking Hip:** decreased abduction 3/5
- **Non-kicking Knee:** increased flexion 4/5; range of flexion 1/5
- **Head – trunk:** increased forward flexion 2/5; decreased forward flexion 1/5; increased left flexion 4/5
- **Head – upper back:** increased left flexion 3/5
- **Lower back – pelvis:** increased left flexion 1/5; decreased left flexion 1/5; range of flexion 1/5; decreased CW rotation 3/5
- **Pelvis – trunk:** increased aCW rotation 3/5
5.4 TKD kinetic results

Kinetic data for the TKD subjects are presented for all three kicks as either one or no feet were on the floor (§4.4.4). Data were scaled in time and normalised by body mass as described in §4.5.6.

5.4.1. Qualitative comparison of joint moments

Initially a qualitative inspection of the moment curves was conducted to identify any obvious similarities or differences between modes. Tables 5.16 to 5.18 show the main differences between the moment curves for normal and 100% modes of execution for each subject (fig. 4.24 and 4.25). The tables illustrate noticeable differences in magnitudes and variability of the curves. Similarly, for the phasing (§2.2.2), comments were made on whether the temporal characteristics were less or more uniform in the 100% mode execution. Moments after contact of kick 3 appeared to become quite varied between trials, presumably because following contact of this last kick, the subjects may no longer have focussed on the performance. In these tables, moments for the kicking leg are followed by moments for the non-kicking leg and finally by moments for the central segments.
Table 5.16: Qualitative description of differences of moment curves in 100% mode compared to normal mode for TKD kick 1 (↑ increase; ↓ decrease; M magnitude; t temporal characteristics; C target contact; neg negative; pos positive). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Hip</td>
<td>↑ neg @ C</td>
<td>↑ M uniform @ / after C</td>
<td>-</td>
<td>no second minimum after C</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↑ t uniform</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>↑ pos @ C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Left Knee</td>
<td>-</td>
<td>-</td>
<td>↑ pos after C</td>
<td>↑ t/M uniform @ C</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↑ pos @ C</td>
</tr>
<tr>
<td>Right Hip</td>
<td>↑ pos @ C; ↑ neg after C</td>
<td>↑ neg @ C</td>
<td>↑ pos @ /after C</td>
<td>no second minimum after C</td>
</tr>
<tr>
<td></td>
<td>↑ neg @ C</td>
<td>↑ neg @ C</td>
<td>↓ t/M uniform @ C</td>
<td>↑ neg @ C</td>
</tr>
<tr>
<td>Right Knee</td>
<td>↑ neg @ C</td>
<td>↑ M uniform after C</td>
<td>↑ neg @ C</td>
<td>↑ M uniform @ C</td>
</tr>
<tr>
<td></td>
<td>↑ neg @ C</td>
<td>↑ M uniform after C</td>
<td>↓ t/M uniform @ /after C</td>
<td>↑ neg @ C</td>
</tr>
<tr>
<td></td>
<td>↑ neg @ C</td>
<td>↑ M uniform after C</td>
<td>↑ neg @ C</td>
<td>↑ neg before C</td>
</tr>
<tr>
<td>TOPJC</td>
<td>↑ neg @ C</td>
<td>↑ t/M uniform @ /after C</td>
<td>↑ neg @ C</td>
<td>↑ neg before C</td>
</tr>
<tr>
<td>(neck)</td>
<td>-</td>
<td>-</td>
<td>↑ neg @ C</td>
<td>↑ pos before C</td>
</tr>
<tr>
<td>MIDJC</td>
<td>Additional neg peak after C</td>
<td>↓ M uniform @ C</td>
<td>↑ neg @ C</td>
<td>↑ t/M uniform</td>
</tr>
<tr>
<td>(upper back)</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↓ M uniform @ C</td>
<td>-</td>
</tr>
<tr>
<td>LOWJC</td>
<td>↑ neg after C</td>
<td>↓ pos after C</td>
<td>Longer neg period after C</td>
<td>↑ neg @ C</td>
</tr>
<tr>
<td>(lower back)</td>
<td>↑ neg @ C</td>
<td>-</td>
<td>↑ pos after C</td>
<td>↑ neg @ C</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↑ neg @ C</td>
</tr>
</tbody>
</table>

Note: entries in the table refer to how moment curves for all trials in 100% mode differ from those in normal mode; see figures 4.22 and 4.23 for examples. For kinetic hierarchy and segments used to calculate moments at these joints refer to §4.4.4, figure 4.7 and table 4.4.
Table 5.17: Qualitative description of differences of moment curves in 100% mode compared to normal mode for TKD kick 2 (↑ increase; ↓ decrease; M magnitude; t temporal characteristics; C target contact; neg negative; pos positive)

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right Hip</strong></td>
<td>↑ neg after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ neg after C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>↓ t uniform @ / after C</td>
<td>↓ t uniform @ / after C</td>
<td>↓ t uniform @ / after C</td>
<td>↑ neg @ C</td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td>↑ pos after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ pos after C</td>
</tr>
<tr>
<td></td>
<td>↑ pos before/after; neg @ C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>↑ pos @ C</td>
</tr>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td></td>
<td>events happen earlier</td>
<td>↑ M uniform @ / after C</td>
<td>↑ M uniform @ / after C</td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td></td>
<td>events happen earlier</td>
<td>↑ M uniform @ / after C</td>
<td>↑ M uniform @ / after C</td>
</tr>
<tr>
<td><strong>TOPJC</strong></td>
<td>↑ neg before C; ↑ pos after C</td>
<td>↑ M uniform @ / after C</td>
<td>↑ neg after C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(neck)</td>
<td>↓ M uniform before C</td>
<td>↓ M uniform before C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MIDJC</strong></td>
<td>↓ pos before; ↑ neg @ C</td>
<td></td>
<td>↑ pos before; ↓ neg @ C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(upper back)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LOWJC</strong></td>
<td>↑ pos after C</td>
<td></td>
<td></td>
<td>↑ M uniform before C</td>
<td></td>
</tr>
<tr>
<td>(lower back)</td>
<td>↓ pos before; ↑ pos after C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: entries in the table refer to how moment curves for all trials in 100% mode differ from those in normal mode; see figures 4.22 and 4.23 for examples. For kinetic hierarchy, and segments used to calculate moments at these joints refer to §4.4.4, figure 4.7 and table 4.4.
Table 5.18: Qualitative description of differences of moment curves in 100% mode compared to normal mode for TKD kick 3 (↑ increase; ↓ decrease; M magnitude; t temporal characteristics; C target contact; neg negative; pos positive)

<table>
<thead>
<tr>
<th></th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hip</strong></td>
<td>-</td>
<td>-</td>
<td>↑ pos @ C</td>
<td>-</td>
<td>↑ t/M uniform @ C &amp; ↑ uniform @ C &amp;</td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td>↓ M uniform</td>
<td>-</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↑ pos &amp; ↑ t uniform @ C &amp;</td>
</tr>
<tr>
<td><strong>Right Hip</strong></td>
<td>↑ pos before C</td>
<td>↑ pos out of K2</td>
<td>↓ M uniform</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td>↑ neg @ C; rapid drop after ↑ neg after C</td>
<td>-</td>
<td>↑ neg after C</td>
<td>↑ pos after C</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOPJC</strong> (neck)</td>
<td>↑ M uniform</td>
<td>↑ pos after C</td>
<td>↓ M uniform @ / after C</td>
<td>-</td>
<td>↓ t/M before/ @ / after C</td>
</tr>
<tr>
<td><strong>MIDJC</strong> (upper back)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>↓ M uniform @ / after C</td>
</tr>
<tr>
<td><strong>LOWJC</strong> (lower back)</td>
<td>↑ neg after C</td>
<td>↑ pos coming out of K2</td>
<td>↑ M uniform</td>
<td>-</td>
<td>↓ M uniform @ / after C &amp;</td>
</tr>
</tbody>
</table>

Note: entries in the table refer to how moment curves for all trials in 100% mode differ from those in normal mode; see figures 4.22 and 4.23 for examples. For kinetic hierarchy and segments used to calculate moments at these joints refer to §4.4.4, figure 4.7 and table 4.4.
From tables 5.16 to 5.18, it can be seen that differences between normal and 100% modes were most noticeable in the central segments and to a lesser extent in the non-kicking leg for kick 1 and kick 3 and in the kicking leg for kick 2, especially in TKD2. In some joints, the moment patterns showed more variability in the 100% execution than in the normal mode execution.

5.4.2. Quantitative variability in joint moments

To further examine these qualitative findings the moment time histories were interpolated to a common time base (§4.5.6) and the standard deviation time histories were calculated and compared between execution modes for each kick (tables 5.19 to 5.21). moment curves with a statistically greater standard deviation (p ≤ 0.05) were assumed to be more variable. The variability of the moment throughout the duration of the kick was relevant as any observed kinematic differences at target contact may be due to moments that occur over a certain time period rather than at a given instant in time. For each joint there is a y, x and z entry in line with the angle definitions (§4.4.6 and §4.4.3).

Table 5.19: Execution mode with largest statistically significant difference in the standard deviations (p ≤ 0.05) of the moment curves for TKD kick 1. For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Axis</th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicking Leg</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Left Hip</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>x</td>
<td>100%</td>
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<td>z</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Left Knee</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
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</tr>
<tr>
<td>Non-kicking Leg</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Hip</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
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<td>100%</td>
<td>100%</td>
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<td>x</td>
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<td>100%</td>
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</tr>
<tr>
<td>Right Knee</td>
<td>y</td>
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<tr>
<td>Trunk</td>
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</tr>
<tr>
<td>TOPJC</td>
<td>y</td>
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<tr>
<td>MIDJC</td>
<td>y</td>
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<td>z</td>
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<td>100%</td>
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</tr>
<tr>
<td>LOWJC</td>
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<td>100%</td>
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<tr>
<td></td>
<td>z</td>
<td>100%</td>
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<td>100%</td>
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</tr>
</tbody>
</table>
Table 5.20: Execution mode with largest statistically significant difference in the standard deviations (p ≤ 0.05) of the moment curves for TKD kick 2. For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Axis</th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Hip</td>
<td>y</td>
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<td>100%</td>
<td>-</td>
<td>100%</td>
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<tr>
<td></td>
<td>x</td>
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<td>z</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Right Knee</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
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<td>100%</td>
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<tr>
<td>Non-kicking Leg</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Left Hip</td>
<td>y</td>
<td>100%</td>
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<td>100%</td>
<td>normal</td>
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<tr>
<td>Left Knee</td>
<td>y</td>
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<tr>
<td>TopJC</td>
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<tr>
<td>MidJC</td>
<td>y</td>
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<td>100%</td>
<td>normal</td>
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</tr>
</tbody>
</table>

Table 5.21: Execution mode with largest statistically significant difference in the standard deviations (p ≤ 0.05) of the moment curves for TKD kick 3. For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Axis</th>
<th>TKD1</th>
<th>TKD2</th>
<th>TKD3</th>
<th>TKD4</th>
<th>TKD5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicking Leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Hip</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
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<td>100%</td>
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<td></td>
<td>x</td>
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<td></td>
<td>z</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>normal</td>
<td>100%</td>
</tr>
<tr>
<td>Left Knee</td>
<td>y</td>
<td>100%</td>
<td>normal</td>
<td>100%</td>
<td>100%</td>
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<td>x</td>
<td>100%</td>
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<td>z</td>
<td>100%</td>
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<td>100%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Non-kicking Leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Hip</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>normal</td>
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<td>z</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
<td>normal</td>
<td>100%</td>
</tr>
<tr>
<td>Right Knee</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
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<tr>
<td>TopJC</td>
<td>y</td>
<td>-</td>
<td>-</td>
<td>100%</td>
<td>normal</td>
<td>-</td>
</tr>
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<td>x</td>
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<td>normal</td>
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<td>z</td>
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<td>100%</td>
<td>normal</td>
<td>100%</td>
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</tr>
<tr>
<td>MidJC</td>
<td>y</td>
<td>100%</td>
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<td>100%</td>
<td>normal</td>
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<td>z</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>normal</td>
<td>100%</td>
</tr>
<tr>
<td>LowJC</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>normal</td>
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<td></td>
<td>z</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
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<td>100%</td>
</tr>
</tbody>
</table>

The above tables show that generally the moment curves of the 100% mode of execution showed more variability than those of the normal mode. The same trends were also observed when analysing the variability up to target contact and from target contact
separately. The average moment time histories for each kick were not significantly different between execution modes.

5.4.3. Joint moments of the kicking leg

The average peak extensor moments at the hip and average peak flexor moments at the knee of the kicking leg were determined for each kick in table 5.22. The table indicates that moments for kick 2 were largest as expected, since the kicking leg travelled furthest in this kick, thus allowing for more force development in the muscle. Kick 1 had higher moments than kick 3 even though the kicks were quite similar. This was presumable due to kick 3 being executed whilst the athletes were airborne. The table also shows that generally moments increased in 100% mode. On few occasions they decreased and this tended to be for kick 3. For kick 1 average hip extensor moments ranged from 89 to 200 Nm and average knee flexor moments ranged from 54 to 117 Nm. For kick 2 average hip extensor moments ranged from 155 to 351 Nm and average knee flexor moments ranged from 95 to 151 Nm. For kick 3 average hip extensor moments ranged from 88 to 142 Nm and average knee flexor moments ranged from 45 to 83 Nm.
Table 5.22: Average normalised peak moments (Nm/kg) and absolute ranges of average peak moments (Nm) of the kicking leg for TKD athletes for the three kicks for both modes of execution.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Execution mode</th>
<th>Hip Extensor Moment (Nm/kg)</th>
<th>Knee Flexor Moment (Nm/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K1</td>
<td>K2</td>
</tr>
<tr>
<td>TKD1</td>
<td>Normal</td>
<td>2.61</td>
<td>3.87</td>
</tr>
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<td>100%</td>
<td>2.95</td>
<td>4.18</td>
</tr>
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<td>TKD2</td>
<td>Normal</td>
<td>1.23</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>1.32</td>
<td>2.14</td>
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<td>TKD3</td>
<td>Normal</td>
<td>2.74</td>
<td>3.66</td>
</tr>
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<td>100%</td>
<td>3.05</td>
<td>3.76</td>
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<td>Normal</td>
<td>1.52</td>
<td>3.62</td>
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<td>100%</td>
<td>1.60</td>
<td>3.75</td>
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<td>TKD5</td>
<td>Normal</td>
<td>2.69</td>
<td>4.68</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>2.97</td>
<td>5.23</td>
</tr>
<tr>
<td>Absolute Range (Nm)</td>
<td>89 – 200 Nm</td>
<td>155 – 351 Nm</td>
<td>88 – 142 Nm</td>
</tr>
</tbody>
</table>
5.4.4. Generic kinetic observations

Although individuality became apparent between the moments of each subject there were certain trends that were observed for all subjects. Certain moment patterns between execution modes when executing the kicking combination were highly repeatable with little variability whereas others were not. The magnitudes of certain peaks particularly in the kicking leg and in the trunk sections tended to be larger although the generic pattern was maintained. Moments of the kicking leg for all subjects and kicks were very consistent between modes. Generally, the variability in 100% mode was higher than that in normal mode.

Generally speaking, moments became more variable after kick contact of kick 1 and kick 2, which was more noticeable at certain joints. In the 100% mode this increased variability between kick 2 to kick 3 may be more pronounced as both legs became airborne and reversed roles (§4.4.4). There were some large standard deviations towards the end of kick 3 but these were due to the combination ending as noted previously (§5.4.1).

For kicks 1 and 3 there seemed no indication of proximal-distal sequencing of the moments of the kicking leg (§2.2.9); however this was present for kick 2 in some subjects (fig. 5.4). Previous research had recorded hip extensor and knee flexor peaks shortly before target contact (Robertson et al., 2004) but data in this study showed these peaks to occur at contact for kick 1 and kick 3 or when there was proximal-distal sequencing for kick 2 the knee peak occurred after contact.

During kick 1, all subjects showed an extensor peak of the kicking hip and a flexor peak of the kicking knee at kick contact. All subjects showed the least variability in the joint moments of the kicking leg. The longitudinal rotator moment of the kicking hip demonstrated noticeably more variability than other moments at the hip especially in 100% mode. The largest variability increase in 100% mode for all subjects was seen in the central sections primarily in lateral directions and to some extent in forward-backward flexion-extension of the upper and lower back. The longitudinal rotator moment of the neck appeared to demonstrate a relatively large variability when compared to other moments of the neck. Moments about all axes of the upper back showed a marked increase in variability after kick contact for both execution modes, but this was even more pronounced in 100% mode, and a similar observation was made for flexor-extensor moments of the lower back. TKD3 actually demonstrated a reduction of variability in upper back lateral moments in 100% mode. No obvious differences between modes were
detected in longitudinal rotator moments of the back segments which had very low variability leading up to kick contact.

![Graphs showing hip extensor and knee flexor moments for TKD kicks 1 and 2.](image)

Figure 5.4: Sequencing of hip extensor moment peak (top) and knee flexor moment peak (bottom) of the kicking leg for TKD kick 1 (A) where they both occur on target contact (0 relative time) and for the TKD kick 2 (B) where the hip extensor peak before the knee flexor peak after target contact (1 relative time) (left curve is for normal mode and right curve is for 100% mode)

During kick 2, all subjects demonstrated an extensor peak of the kicking hip followed by a knee flexor peak which could occur after kick contact. The abductor-adductor and flexor-extensor moments of the kicking hip became quite varied after kick contact in 100% mode. Similarly, the peak flexor moments of the kicking knee demonstrated much more variation in 100% mode. The longitudinal moment of the non-kicking hip showed marked variability after kick contact and the flexor-extensor moment of the non-kicking knee showed a high degree of variability throughout the kick, which became more pronounced in 100% mode for some subjects. Longitudinal rotator moments of the upper and lower back were very consistent in all subjects. In some cases the variability in 100% mode was
even lower than that observed in normal mode. Moments at the neck and flexor-extensor moments for the lower back were quite varied throughout the kick.

During kick 3, all subjects showed an extensor peak of the kicking hip and a flexor peak of the kicking knee at kick contact. Moments in all directions of the non-kicking knee were markedly more varied after kick contact, particularly in 100% mode. Longitudinal rotator moments of the upper and lower back again appeared very consistent. Lateral moments of the upper and lower back were most variable in this kick. The lateral flexor-extensor moments for the upper back were quite varied throughout the kick. In the lower back the variability differences were subject specific. The longitudinal rotator and lateral flexor moments of the neck seemed to show an increase in variability in most subjects.

5.4.5. Variability in joint moment time histories

To gain a better understanding of where in the curves the locus of variability lies, the average moment time histories (mean ± standard deviation) of both modes were plotted. These are presented for certain cases in figures 5.5-5.65 where the y axis intersects the x axis at kick contact. For kick 1 this is at 0 MT1; for kick 2 this is at 1 MT1; and for kick 3 this is at 1 MT2 (§4.5.6). The titles for each figure indicate the subject and the kick first, followed by a description of the moment. The complete set of average moment curves for all subjects, joints, kicks and execution modes is given Appendix 6.

The graphs show that the gross patterns of the moment curves were preserved between execution modes. Sometimes peak amplitudes were noticeably higher in the 100% mode (fig. 5.7b). The width of the standard deviation bands tended to be bigger in 100% mode which supported the statistical analysis of the variability (tables 5.19-5.21). The curves showing the greatest and least marked differences between modes of executions for each subject are presented below.

The time histories of the difference in variability of the 100% mode and the normal mode showed fluctuations over the analysed time periods. Three main groups can be distinguished: the difference remains predominantly positive, i.e. 100% mode always shows more variability; the difference remains predominantly negative, i.e. normal mode always shows more variability; or the difference fluctuates between positive and negative.
For this subject the least variability in kick 1 was seen in the moments of the kicking leg (fig. 5.5). Most marked changes were observed in the non-kicking leg and certain areas of the trunk. The hip flexor and extensor peaks were greater in 100% mode (fig. 5.6). Further changes were observed at the non-kicking knee where a drop in varus moment is accompanied by an increased extensor and internal rotator moment (fig. 5.7a, b, c). The lateral moments at the neck more were negative (left flexor) throughout the kick (fig. 5.8a). The lateral moments in the other areas of the central segments showed a higher second positive peak after kick contact in 100% mode (fig. 5.8b, c). The extensor moments in the back were greater and appeared later in time (fig. 5.9a, b).

The most prominent changes between execution modes in kick 2 were the larger standard deviation in 100% mode even though the average moment curves showed minimal global differences. Very low variability was observed in the longitudinal rotator moments of the back segments especially in normal mode (fig. 5.10). In normal mode the majority of the moments leading up to kick contact demonstrated low standard deviations yet in the 100% mode it was quite apparent (fig. 5.11). Specific changes were now mostly observed in the kicking leg. The adductor moment of the hip (fig. 5.11a) and the varus moment at the knee (fig. 5.12) at kick contact showed a pronounced range of standard deviation. In the trunk there was a change in the lateral flexor moment of the lower back. The larger peak occurred after contact in 100% mode, whereas it occurred before contact in normal mode (fig. 5.13). No other obvious changes were found in the trunk sections which was to be expected as this kick is very planar in its execution compared to the other two kicks.
Figure 5.5: TKD1 K1 kicking knee flexor-extensor moments: low variability

Figure 5.6: TKD1 K1 non-kicking hip flexor-extensor moment

Figure 5.7: TKD1 K1 non-kicking knee moments

a. valgus-varus  
b. flexor-extensor  
c. internal-external rotator
Figure 5.10: TKD1 K2 longitudinal rotator upper back: low variability

Figure 5.11: TKD1 K2 kicking hip moments

a. abductor-adductor moment
b. flexor-extensor moment

Figure 5.12: TKD1 K2 kicking knee valgus-varus moments

Figure 5.13: TKD1 K2 lower back lateral flexor moments
Kick 3 showed the best consistency between modes. Surprisingly the longitudinal rotator moments of the trunk segments showed relatively little variation (fig. 5.14a). The moments related to lateral flexion however showed a lot of variation in both modes (fig. 5.14b). The variation of moments of the non-kicking leg was higher than in normal mode where it was almost absent about certain axes (fig. 5.14 left panel). Moments of the kicking leg were higher around contact in 100% mode and the biggest difference could be seen in the knee flexor moment (fig. 5.16).
TKD2

Generally, the variability in 100% mode was higher than that in normal mode. This subject demonstrates the least variability for kick 1 in the moments of the kicking leg (fig. 5.17). The rotator moment of the hip showed large variability when transferring from kick 1 to kick 2 in 100% mode (fig. 5.18). Most marked changes were observed about lateral axes in areas of the trunk (fig. 5.19) and neck. The neck also showed large variability in longitudinal rotation when transferring from kick 1 to kick 2 (fig. 5.20).

In kick 2 TKD2 did not demonstrate huge increases in standard deviations like TKD1. However, generally the standard deviation bands were larger in 100% mode. Again, very low variability was observed in the longitudinal rotator moments of the back segments especially in the lower back (fig. 5.21). In normal mode the majority of the moments leading up to kick contact hardly demonstrated any standard deviation at all yet in the 100% mode it was apparent (fig. 5.22). The most variation for this subject was seen in the flexor moments of the non-kicking leg after kick contact when progressing to kick 3 (fig. 5.23) and in the neck longitudinal rotator moment coming out of kick 1 (fig. 5.24). It appeared that for the neck and lower back the standard deviation bands in longitudinal rotation were relatively large coming out of kick 1 and then become quite narrow leading up to kick 2. For the upper back this was not so pronounced. When leading up to kick 3 the bands for the upper and lower back stayed relatively narrow, yet at the neck they became relatively large again.

During kick 3 this subject had less or the same variability in 100% mode of moments in the kicking leg as can be seen from the hip abductor and knee flexor moments (fig. 5.25, table 5.21). This was also true for certain areas of the curves in the non-kicking leg (5.26). Large variability was seen at the neck in lateral and longitudinal rotator moments (fig. 5.27) and at the lower back in lateral moments (5.28).
Figure 5.17: TKD2 K1 kicking leg moments: low variability

![Graphs showing low variability in kicking leg moments for TKD2 K1.]

- a. abductor-adductor moment of the hip
- b. flexor-extensor moment of the knee

Figure 5.18: TKD2 K1 kicking hip longitudinal moments

![Graphs showing kicking hip longitudinal moments for TKD2 K1.]

Figure 5.19: TKD2 K1 back segments lateral moments: marked variability

![Graphs showing marked variability in back segments lateral moments for TKD2 K1.]

- a. upper back
- b. lower back

Figure 5.20: TKD2 K1 neck longitudinal moments: large variability

![Graphs showing large variability in neck longitudinal moments for TKD2 K1.]

![Graphs showing neck longitudinal moments for TKD2 K1.]

- a. upper back
- b. lower back
Figure 5.21: TKD2 K2 back segments longitudinal moments: low variability

Figure 5.22: TKD2 K2 kicking hip flexor-extensor moments

Figure 5.23: TKD2 K2 non-kicking leg flexor moments

Figure 5.24: TKD2 K2 neck longitudinal moments

a. lower back

b. upper back

a. hip

b. knee
Figure 5.25: TKD2 K3 kicking leg moments: reduction in variability

a. hip abductor-adductor

b. knee flexor-extensor

Figure 5.27: TKD2 K3 neck moments: marked variability

a. lateral flexor

b. longitudinal rotator

Figure 5.26: TKD2 K3 non-kicking knee varus moments: reduction in variability

Figure 5.28: TKD2 K3 lower back lateral flexor moments
In kick 1 least variability was again shown in moments for the kicking leg (fig. 5.29). Slightly more variation was seen in moments of the non-kicking leg, particularly those associated with longitudinal rotation where a lower positive moment at the hip caused a sustained positive moment at the knee (fig. 5.30). The most pronounced changes could be seen in the central segments. The longitudinal moments of the neck were increased and showed more variability leading up to the kick (fig. 5.31). Interestingly, moments in lateral directions in the upper back seemed to become more consistent in 100% mode (fig. 5.32). There was an obvious change in lateral flexor moments (fig. 5.33) and to some extent in the forward-backward flexor moments of the lower back.

This subject displayed very little change between the two modes for kick 2 (table 5.20). The lowest variability was observed in the kicking leg, particularly the hip (fig. 5.34). It was also quite clear that the standard deviations for the abduction and longitudinal rotation of the hip diminished markedly at times. This phenomenon was also present in the knee (fig. 5.35). Longitudinal rotation of the upper and particularly the lower back were again very consistent. Most variation was seen at moments for the neck (fig. 5.36).

In kick 3 least variability was seen in the flexor-extensor moments of the kicking leg (fig. 5.37). The flexor moment of the knee decreased in 100% mode (fig. 5.37b). Generally, moments tended to become more varied after completion of kick 3 especially in the longitudinal rotation of the non-kicking leg (fig. 5.38). Most variability was again observed in the central segments especially after kick contact. Variations of moments about the neck seemed to be more pronounced in lateral directions but less so in longitudinal rotation in 100% mode. The lower back showed a marked increase in variability in backward extension and longitudinal rotation (fig. 5.39). The increase in variability in backward extension was also present in the upper back (fig. 5.40).
Figure 5.29: TKD3 K1 kicking knee flexor moments: low variability

Figure 5.30: TKD3 K1 non-kicking leg longitudinal moments

Figure 5.31: TKD3 K1 neck longitudinal moments

Figure 5.32: TKD3 K1 upper back lateral moments

Figure 5.33: TKD3 K1 lower back lateral moments
Figure 5.34: TKD3 K2 kicking hip flexor-extensor moments

Figure 5.35: TKD3 K2 kicking knee valgus-varus moments

Figure 5.36: TKD3 K3 neck moments

a. lateral flexor
b. forward-backward flexor
c. longitudinal rotator
Figure 5.37: TKD3 K3 kicking leg flexor-extensor moments

Figure 5.38: TKD3 K3 non-kicking knee longitudinal moments

Figure 5.39: TKD3 K3 lower back moments

Figure 5.40: TKD3 K3 upper back flexor-extensor moments

a. hip
b. knee

a. forward/backward flexor
b. longitudinal rotator
TKD4

Not many obvious changes could be detected in kick 1 for this subject. Moments and variability of both legs were comparable between modes. Least variability was again seen in the kicking leg especially in the hip abductor-adductor moments (fig. 5.41). The longitudinal rotator moment of the kicking hip showed a change in timing and amplitude in 100% mode around kick contact (fig. 5.42). The forward-backward flexor and lateral flexor moments of the upper (fig. 5.43) and lower (fig. 5.44) back showed slight changes in amplitudes of the moments and their variabilities especially when progressing to kick 2.

In kick 2 most variability was seen in the lower back forward-backward flexion-extension (fig. 5.45a). There was virtually no variation in longitudinal rotation, but there was some in lateral moments (fig. 5.45b, c). The upper back showed a reduction in variability in forward-backward flexor-extensor moments and a greater extensor peak leading up to kick contact (fig. 5.46). Lateral and longitudinal rotator moments of the upper back showed very little variation. There was hardly any variability in the kicking leg about any axis in either mode (fig. 5.47). The moments of the non-kicking legs also showed relatively little variability although it seemed to increase towards kick 3 especially at the hip (fig. 5.48).

Kick 3 seemed to have more overall variability compared to other kicks for this subject. The flexor-extensor moments of the kicking hip appeared to be the least variable leading up to kick contact (fig. 5.49). In the back segments the longitudinal rotator moments had the lower variability (fig. 5.50). However, the lateral rotator moments demonstrated high variability in both modes and were on average higher in 100% mode (fig. 5.51). The longitudinal rotator moment of the neck also demonstrated wide bands of variability which improved around kick contact in 100% mode (fig. 5.52).
Figure 5.41: TKD4 K1 kicking hip abductor-adductor moments

Figure 5.42: TKD4 K1 kicking hip longitudinal moments

Figure 5.43: TKD4 K1 upper back moments

Figure 5.44: TKD4 K1 lower back moments
Figure 5.45: TKD4 K2 lower back moments

a. flexor-extensor  
b. lateral flexor  
c. longitudinal rotator

Figure 5.46: TKD4 K2 upper back flexor-extensor

Figure 5.47: TKD4 K2 kicking knee flexor-extensor  
Figure 5.48: TKD4 K2 non-kicking hip abductor-adductor
Figure 5.49: TKD4 K3 kicking hip flexor-extensor moments

Figure 5.50: TKD4 K3 back segments longitudinal moments

Figure 5.51: TKD4 K3 back segments lateral moments

Figure 5.52: TKD4 K3 neck longitudinal moments
TKD5

In general, kick 1 showed very little variability for this subject in both modes especially in the knees and hips of both legs (fig. 5.53). The variabilities of the non-kicking hip abductor-adductor moments (fig. 5.54) and the upper back lateral flexor moments (fig. 5.55) actually showed a reduction in variability after kick contact in 100% mode. Most variability was seen in the lower back although the variability in forward flexor-extensor moment was the only moment to increase variability in 100% mode (fig. 5.56).

In kick 2 there were also very little variations in general. For the kicking leg the moments leading up to contact and those just after contact showed hardly any variation at all. At contact there was some minimal variability (fig. 5.57). The forward-backward flexor-extensor moments of the back showed the biggest variability which increased in 100% mode (fig. 5.58). There was a noticeable increase in the non-kicking hip abductor moment in 100% mode (fig. 5.59). The longitudinal rotator moment of the lower back showed less variability leading up to kick contact in 100% mode (fig. 5.60). The longitudinal rotator moment of the neck showed bigger fluctuations in 100% mode (fig. 5.61).

In kick 3 this subject displayed marked increases in variability in 100% mode in all moments although those of the kicking leg were still the least variable (fig. 5.62). Although variability increases in all moments of the back, the most marked increases and pattern changes were shown in lateral flexor moments (fig. 5.63). Additionally, the longitudinal rotator moment of the lower back showed a marked increase in variability (fig. 5.64). Abductor-adductor moments of the non-kicking hip and valgus-varus moments of the non-kicking knee showed little variability in normal mode but a wide range in 100% mode (fig. 5.65).
Figure 5.53: TKD5 K1 kicking knee flexor-extensor

Figure 5.54: TKD5 K1 non-kicking hip abductor-adductor

Figure 5.55: TKD5 K1 upper back lateral moments

Figure 5.56: TKD5 K1 lower back moments

a. forward-backward flexor-extensor

b. lateral flexor

c. longitudinal rotator
Figure 5.57: TKD5 K2 kicking knee flexor-extensor

Figure 5.58: TKD5 K2 back segments forward-backward flexor-extensor moments

Figure 5.59: TKD5 K2 non-kicking hip abductor-adductor

Figure 5.60: TKD5 K2 lower back longitudinal moments

Figure 5.61: TKD5 K2 neck longitudinal moments
Figure 5.62: TKD5 K3 kicking hip abductor-adductor

Figure 5.63: TKD5 K3 back segments lateral flexor moments

Figure 5.64: TKD5 K3 lower back longitudinal moments

Figure 5.65: TKD5 K3 non-kicking leg abductor-adductor and valgus-varus moments
5.5 TKD approximate entropy

The approximate entropy (ApEn) (Pincus, 1991) was calculated for all unfiltered joint angle time histories throughout each technique (§4.5.7). This value gave an indication of how ordered the signal, in this case the joint angles, was for the duration of a trial. If the signal was highly ordered the ApEn will be close to 0; the more chaotic the signal the higher the ApEn value. The average ApEn value for each joint axis was compared between execution modes. The general ranges of the calculated ApEn for each technique and body section are shown in table 5.23.

Table 5.23: Ranges of approximate entropy averages for all joint angles for all TKD trials (§4.5.7) (calculated with run length 2 and filter length 0.5)

<table>
<thead>
<tr>
<th></th>
<th>Legs</th>
<th>Central segments</th>
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</thead>
<tbody>
<tr>
<td>Kick 1</td>
<td>0.06 – 0.56</td>
<td>0.06 – 0.56</td>
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<tr>
<td>Kick 2</td>
<td>0.07 – 0.47</td>
<td>0.07 – 0.53</td>
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<tr>
<td>Kick 3</td>
<td>0.01 – 0.38</td>
<td>0.02 – 0.51</td>
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</table>

When comparing the ApEn for both execution modes they were generally comparable for each joint axis. A comparison of ApEn values between execution modes is given in table 6.24, which gives the mode with significantly higher ApEn (p ≤ 0.05). The first entry pertains to the y axis, the second to the x axis and the third to the z axis (§4.4.3; Appendix 2 for axes definitions).
Table 5.24: Performance mode with significantly higher approximate entropy of joint angle time histories (p \( \leq 0.05 \)) for the legs and trunk for TKD athletes (norm = normal mode; 100\% = 100\% mode)

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<th>TKD1</th>
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<th>TKD4</th>
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<th>TKD5</th>
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<td>Head-Trunk</td>
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<td>Head-Upper back</td>
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<td>Upper back – lower back</td>
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<td>Lower back – pelvis</td>
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<td>Upper back – Pelvis</td>
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<td>Pelvis – Trunk</td>
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Chapter 6

RESULTS 2 – KARATE DATA

6.1 Chapter outline

This chapter shows the results for the karate subjects. First, the data relevant to determining the instant in time at which target contact occurred is presented. Then, kinematic and target acquisition results are presented. The first set of kinematic results pertains to the durations, distances, and velocities of the whole combination as well as its individual components of both modes of execution. The second set of kinematic results pertains to the contact timing, the linear fist and foot velocity and the stretch within individual techniques for both modes of execution. The last set presents joint angle differences at target contact between modes of execution. The kinetic results follow, which compare joint moment patterns between execution modes. As kinetic data for the punching techniques of the combination were unreliable due to the subject either having both feet on the floor, or the timing of one foot landing on or leaving the floor being inconsistent ($§4.4.4$) the approximate entropy ($\text{ApEn}$) of joint angles histories was calculated and compared for both modes and these data are presented last. In the tables P1, P2 and Kk refer to punches 1 and 2 and the kick of the karate combination.

6.2 Karate target pad contact determination

Table 6.1 shows the average time differences between the manually determined instant of contact and the instant of peak acceleration of the pad marker for forty randomly selected target impacts.

Table 6.1: Karate time difference between the instant of target contact and impact for each subject (average ± standard deviation)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Time difference (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>13 ± 5</td>
</tr>
<tr>
<td>KAR2</td>
<td>13 ± 4</td>
</tr>
<tr>
<td>KAR3</td>
<td>13 ± 5</td>
</tr>
<tr>
<td>KAR4</td>
<td>11 ± 4</td>
</tr>
<tr>
<td>KAR5</td>
<td>13 ± 7</td>
</tr>
</tbody>
</table>
As data were captured at 480Hz the above time differences are equivalent to approximately 5 or 6 time-frames ± 2 time-frames. Hence, the instant in time of contact was defined as 6 time-frames before the time of impact, i.e. 12.5 ms. Based on this definition, the contact point was established for all trials.

6.3 Karate kinematic and target acquisition results

6.3.1. Kinematics 1 - Combination durations, distances and average speeds results

Table 6.2 shows the mean execution times for both modes of execution. Significant differences between modes (p ≤ 0.05) are indicated by *.

Table 6.2: Karate execution times (s) (mean ± standard deviation) for all three techniques and for the combination in both modes of execution (N = normal mode; 100 = 100% mode, * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset – P1 N</td>
<td>0.33 ± 0.01</td>
<td>0.21 ± 0.02 *</td>
<td>0.21 ± 0.02</td>
<td>0.30 ± 0.03</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>Onset – P1 100</td>
<td>0.33 ± 0.02</td>
<td>0.20 ± 0.01 *</td>
<td>0.21 ± 0.02</td>
<td>0.31 ± 0.02</td>
<td>0.37 ± 0.04</td>
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<tr>
<td>P1 – P2 N</td>
<td>0.32 ± 0.02 *</td>
<td>0.27 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td>0.29 ± 0.01 *</td>
<td>0.33 ± 0.03 *</td>
</tr>
<tr>
<td>P1 – P2 100</td>
<td>0.30 ± 0.01 *</td>
<td>0.28 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td>0.26 ± 0.02 *</td>
<td>0.30 ± 0.02 *</td>
</tr>
<tr>
<td>P2 – Kk N</td>
<td>0.53 ± 0.02 *</td>
<td>0.47 ± 0.02 *</td>
<td>0.49 ± 0.01</td>
<td>0.45 ± 0.01 *</td>
<td>0.49 ± 0.02 *</td>
</tr>
<tr>
<td>P2 – Kk 100</td>
<td>0.49 ± 0.02 *</td>
<td>0.46 ± 0.01 *</td>
<td>0.48 ± 0.01</td>
<td>0.40 ± 0.02 *</td>
<td>0.47 ± 0.02 *</td>
</tr>
<tr>
<td>Onset – Kk N</td>
<td>1.19 ± 0.03 *</td>
<td>0.95 ± 0.03</td>
<td>1.03 ± 0.02</td>
<td>1.03 ± 0.03 *</td>
<td>1.16 ± 0.07</td>
</tr>
<tr>
<td>Onset – Kk 100</td>
<td>1.12 ± 0.03 *</td>
<td>0.94 ± 0.02</td>
<td>1.02 ± 0.03</td>
<td>0.97 ± 0.03 *</td>
<td>1.13 ± 0.05</td>
</tr>
</tbody>
</table>
As with the TKD subjects, the distance travelled in the combination was expressed as the change in the location of the midpoint vector of both hip joints (table 6.3). However, as the karate subjects also fired techniques with the arms, the distance was also expressed using the midpoint of the shoulder joints (§4.5.2) (table 6.4). The mean execution distances for the combination are shown in mm in tables 6.3 and 6.4. Significant differences between modes (p ≤ 0.05) are indicated by *.

Table 6.3: Karate execution distances (mm) (mean ± standard deviation) of the three techniques and for the total and effective distances of the combination based on the translation of the hips (§4.5.2) (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - P1 N</td>
<td>490 ± 86</td>
<td>433 ± 30</td>
<td>344 ± 64</td>
<td>605 ± 152</td>
<td>567 ± 67 *</td>
</tr>
<tr>
<td>Onset - P1 100</td>
<td>549 ± 38</td>
<td>408 ± 35</td>
<td>355 ± 24</td>
<td>591 ± 55</td>
<td>660 ± 81 *</td>
</tr>
<tr>
<td>P1 - P2 N</td>
<td>759 ± 61</td>
<td>710 ± 54</td>
<td>725 ± 35</td>
<td>790 ± 144</td>
<td>849 ± 113</td>
</tr>
<tr>
<td>P1 - P2 100</td>
<td>735 ± 47</td>
<td>752 ± 38</td>
<td>763 ± 55</td>
<td>697 ± 168</td>
<td>838 ± 69</td>
</tr>
<tr>
<td>P2 - Kk N</td>
<td>1132 ± 63 *</td>
<td>1353 ± 77</td>
<td>853 ± 63 *</td>
<td>966 ± 38</td>
<td>943 ± 107</td>
</tr>
<tr>
<td>P2 - Kk 100</td>
<td>1199 ± 65 *</td>
<td>1373 ± 85</td>
<td>928 ± 90 *</td>
<td>999 ± 163</td>
<td>1009 ± 91</td>
</tr>
<tr>
<td>Effective N</td>
<td>2350 ± 191</td>
<td>2446 ± 100 *</td>
<td>1835 ± 88 *</td>
<td>2276 ± 55</td>
<td>2317 ± 265</td>
</tr>
<tr>
<td>Effective 100</td>
<td>2441 ± 99</td>
<td>2552 ± 105 *</td>
<td>2000 ± 114 *</td>
<td>2219 ± 87</td>
<td>2484 ± 201</td>
</tr>
<tr>
<td>Total N</td>
<td>2364 ± 188</td>
<td>2495 ± 110</td>
<td>1922 ± 106 *</td>
<td>2361 ± 55 *</td>
<td>2358 ± 268</td>
</tr>
<tr>
<td>Total 100</td>
<td>2480 ± 96</td>
<td>2541 ± 127</td>
<td>2045 ± 115 *</td>
<td>2288 ± 87 *</td>
<td>2490 ± 147</td>
</tr>
</tbody>
</table>

Table 6.4: Karate execution distances (mm) (mean ± standard deviation) of the three techniques and for the total and effective distances of the combination based on the translation of the shoulders (§4.5.2) (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - P1 N</td>
<td>543 ± 42 *</td>
<td>456 ± 30</td>
<td>323 ± 49</td>
<td>584 ± 49</td>
<td>642 ± 81 *</td>
</tr>
<tr>
<td>Onset - P1 100</td>
<td>593 ± 43 *</td>
<td>461 ± 38</td>
<td>355 ± 30</td>
<td>624 ± 55</td>
<td>759 ± 93 *</td>
</tr>
<tr>
<td>P1 - P2 N</td>
<td>869 ± 64</td>
<td>850 ± 60</td>
<td>780 ± 51</td>
<td>836 ± 39 *</td>
<td>906 ± 133</td>
</tr>
<tr>
<td>P1 - P2 100</td>
<td>826 ± 31</td>
<td>898 ± 67</td>
<td>823 ± 60</td>
<td>751 ± 54 *</td>
<td>877 ± 81</td>
</tr>
<tr>
<td>P2 - Kk N</td>
<td>699 ± 53</td>
<td>853 ± 92</td>
<td>438 ± 62 *</td>
<td>538 ± 25</td>
<td>655 ± 117</td>
</tr>
<tr>
<td>P2 - Kk 100</td>
<td>835 ± 180</td>
<td>843 ± 77</td>
<td>512 ± 80 *</td>
<td>550 ± 55</td>
<td>713 ± 63</td>
</tr>
<tr>
<td>Effective N</td>
<td>2097 ± 148</td>
<td>2108 ± 120 *</td>
<td>1516 ± 82 *</td>
<td>1919 ± 52</td>
<td>2167 ± 290</td>
</tr>
<tr>
<td>Effective 100</td>
<td>2209 ± 125</td>
<td>2218 ± 103 *</td>
<td>1662 ± 121 *</td>
<td>1895 ± 90</td>
<td>2333 ± 218</td>
</tr>
<tr>
<td>Total N</td>
<td>2114 ± 114</td>
<td>2160 ± 129</td>
<td>1541 ± 85 *</td>
<td>1958 ± 53</td>
<td>2201 ± 304</td>
</tr>
<tr>
<td>Total 100</td>
<td>2246 ± 186</td>
<td>2211 ± 118</td>
<td>1690 ± 119 *</td>
<td>1930 ± 92</td>
<td>2327 ± 134</td>
</tr>
</tbody>
</table>
In order to gain some information of how upright the athletes were during the combination, the hip execution distances from table 6.3 were subtracted from the shoulder execution distances in table 6.4. As differences between effective and total distances were small (table 6.3 and 6.4) the data in table 6.5 was assumed to predominantly be caused by forward-backward lean. These results are given in table 6.5, where a positive value indicates the upper body was leading. Significant differences between modes (p ≤ 0.05) are indicated by *.

Table 6.5: Karate combination difference in execution distances (mm) (mean ± standard deviation) for the three techniques between shoulder JC midpoints and hip JC midpoints (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - P1 N</td>
<td>53 ± 96</td>
<td>23 ± 42 *</td>
<td>-21 ± 81</td>
<td>-21 ± 160</td>
<td>75 ± 105 *</td>
</tr>
<tr>
<td>Onset - P1 100</td>
<td>44 ± 57</td>
<td>53 ± 52 *</td>
<td>0 ± 38</td>
<td>33 ± 78</td>
<td>99 ± 123 *</td>
</tr>
<tr>
<td>P1 - P2 N</td>
<td>110 ± 88</td>
<td>140 ± 81</td>
<td>55 ± 62</td>
<td>46 ± 149</td>
<td>57 ± 175</td>
</tr>
<tr>
<td>P1 - P2 100</td>
<td>91 ± 56</td>
<td>146 ± 77</td>
<td>60 ± 81</td>
<td>54 ± 176</td>
<td>39 ± 106</td>
</tr>
<tr>
<td>P2 - Kk N</td>
<td>-433 ± 82</td>
<td>-500 ± 120</td>
<td>-415 ± 88</td>
<td>-428 ± 45</td>
<td>-288 ± 159</td>
</tr>
<tr>
<td>P2 - Kk 100</td>
<td>-364 ± 191</td>
<td>-530 ± 115</td>
<td>-416 ± 120</td>
<td>-449 ± 172</td>
<td>-296 ± 111</td>
</tr>
</tbody>
</table>

Using the data from tables 6.2 to 6.4, the average movement speeds for each section of the combination could be calculated. The results are shown in tables 6.6 and 6.7. Significant differences between modes (p ≤ 0.05) are indicated by *.

Table 6.6: Karate combination speeds (m/s) for the three techniques and combination based on hip translations (N = normal mode; 100 = 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset - P1 N</td>
<td>1.49 ± 0.27</td>
<td>2.02 ± 0.21</td>
<td>1.62 ± 0.34</td>
<td>2.05 ± 0.55</td>
<td>1.68 ± 0.23 *</td>
</tr>
<tr>
<td>Onset - P1 100</td>
<td>1.65 ± 0.14</td>
<td>2.06 ± 0.23</td>
<td>1.67 ± 0.17</td>
<td>1.88 ± 0.20</td>
<td>1.80 ± 0.25 *</td>
</tr>
<tr>
<td>P1 - P2 N</td>
<td>2.36 ± 0.25 *</td>
<td>2.67 ± 0.27</td>
<td>2.22 ± 0.17 *</td>
<td>2.72 ± 0.51</td>
<td>2.60 ± 0.36 *</td>
</tr>
<tr>
<td>P1 - P2 100</td>
<td>2.47 ± 0.20 *</td>
<td>2.71 ± 0.22</td>
<td>2.33 ± 0.21 *</td>
<td>2.73 ± 0.68</td>
<td>2.83 ± 0.36 *</td>
</tr>
<tr>
<td>P2 - Kk N</td>
<td>2.15 ± 0.14 *</td>
<td>2.86 ± 0.19</td>
<td>1.74 ± 0.13 *</td>
<td>2.17 ± 0.10 *</td>
<td>1.92 ± 0.22 *</td>
</tr>
<tr>
<td>P2 - Kk 100</td>
<td>2.45 ± 0.17 *</td>
<td>3.02 ± 0.20</td>
<td>1.92 ± 0.19 *</td>
<td>2.50 ± 0.43 *</td>
<td>2.15 ± 0.20 *</td>
</tr>
<tr>
<td>Effective N</td>
<td>1.98 ± 0.17 *</td>
<td>2.56 ± 0.13 *</td>
<td>1.78 ± 0.09 *</td>
<td>2.21 ± 0.09 *</td>
<td>2.01 ± 0.23 *</td>
</tr>
<tr>
<td>Effective 100</td>
<td>2.18 ± 0.10 *</td>
<td>2.71 ± 0.12 *</td>
<td>1.95 ± 0.12 *</td>
<td>2.29 ± 0.12 *</td>
<td>2.19 ± 0.20 *</td>
</tr>
<tr>
<td>Total N</td>
<td>2.00 ± 0.17 *</td>
<td>2.62 ± 0.14</td>
<td>1.87 ± 0.11 *</td>
<td>2.29 ± 0.09</td>
<td>2.04 ± 0.24 *</td>
</tr>
<tr>
<td>Total 100</td>
<td>2.21 ± 0.10 *</td>
<td>2.70 ± 0.15</td>
<td>2.00 ± 0.13 *</td>
<td>2.36 ± 0.12</td>
<td>2.20 ± 0.16 *</td>
</tr>
</tbody>
</table>
Table 6.7: Karate combination speeds (m/s) for the three techniques and combination based on shoulder translations (N = normal mode; 100% mode; * is significantly different between modes)

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Onset - P1</strong></td>
<td>1.65 ± 0.14 *</td>
<td>2.13 ± 0.22 *</td>
<td>1.51 ± 0.27 *</td>
<td>1.98 ± 0.25</td>
<td>1.90 ± 0.27 *</td>
</tr>
<tr>
<td><strong>Onset - P1 100</strong></td>
<td>1.79 ± 0.16 *</td>
<td>2.33 ± 0.25 *</td>
<td>1.67 ± 0.19 *</td>
<td>1.99 ± 0.21</td>
<td>2.07 ± 0.29 *</td>
</tr>
<tr>
<td><strong>P1 - P2</strong></td>
<td>2.70 ± 0.27 *</td>
<td>3.20 ± 0.30</td>
<td>2.39 ± 0.21 *</td>
<td>2.87 ± 0.19</td>
<td>2.78 ± 0.42 *</td>
</tr>
<tr>
<td><strong>P1 - P2 100</strong></td>
<td>2.77 ± 0.17 *</td>
<td>3.23 ± 0.31</td>
<td>2.51 ± 0.22 *</td>
<td>2.95 ± 0.29</td>
<td>2.96 ± 0.40 *</td>
</tr>
<tr>
<td><strong>P2 - Kk</strong></td>
<td>1.33 ± 0.11 *</td>
<td>1.80 ± 0.20</td>
<td>0.894 ± 0.13 *</td>
<td>1.21 ± 0.07 *</td>
<td>1.33 ± 0.24 *</td>
</tr>
<tr>
<td><strong>P2 - Kk 100</strong></td>
<td>1.70 ± 0.38 *</td>
<td>1.85 ± 0.17</td>
<td>1.06 ± 0.17 *</td>
<td>1.38 ± 0.16 *</td>
<td>1.52 ± 0.14 *</td>
</tr>
<tr>
<td><strong>Effective N</strong></td>
<td>1.77 ± 0.13 *</td>
<td>2.21 ± 0.14 *</td>
<td>1.47 ± 0.09 *</td>
<td>1.86 ± 0.08 *</td>
<td>1.88 ± 0.25 *</td>
</tr>
<tr>
<td><strong>Effective 100</strong></td>
<td>1.97 ± 0.12 *</td>
<td>2.36 ± 0.12 *</td>
<td>1.62 ± 0.13 *</td>
<td>1.96 ± 0.11 *</td>
<td>2.06 ± 0.21 *</td>
</tr>
<tr>
<td><strong>Total N</strong></td>
<td>1.78 ± 0.10 *</td>
<td>2.26 ± 0.15</td>
<td>1.50 ± 0.09 *</td>
<td>1.90 ± 0.11 *</td>
<td>1.91 ± 0.27 *</td>
</tr>
<tr>
<td><strong>Total 100</strong></td>
<td>2.00 ± 0.17 *</td>
<td>2.35 ± 0.13</td>
<td>1.65 ± 0.13 *</td>
<td>1.99 ± 0.12 *</td>
<td>2.05 ± 0.15 *</td>
</tr>
</tbody>
</table>

### 6.3.2. Kinematics 2 - Detriment, peak and contact velocity and stretch results

Table 6.8 shows the mean detriments, fist and foot velocities and stretches for the two punches and the kick (§4.5.3). Significant differences (p ≤ 0.05) are indicated by *. In contrast to TKD athletes, karate athletes need to demonstrate control of contact with the head (§1.2). This means that punch 1 and the kick should transfer little energy from the fist or foot into the target.
Table 6.8: Karate detriment, peak and contact velocity and stretch data (mean ± standard deviation) for the three techniques of the combination (N = normal mode; 100% = 100% mode; * is significantly different between modes; italics indicate that contact occurred before peak foot velocity was reached)

| Subj. | Mode | Detriment (ms) | Peak Velocity (m/s) | Contact Velocity (m/s) | Contact %stretch | P1 | | Detriment (ms) | Peak Velocity (m/s) | Contact Velocity (m/s) | Contact %stretch | P2 | | Detriment (ms) | Peak Velocity (m/s) | Contact Velocity (m/s) | Contact %stretch | Kk | |
|-------|------|---------------|---------------------|------------------------|-----------------|----| |  |  |  |  | |  |  |  |  |  |  |  |  |  |  |
| KAR1 N 100% | 21 ± 16 | 5.33 | ± 0.54 | 4.84 | ± 0.91 | 76.3 | 8.1 | ± 0.25 | ± 4.6 | ± 1.43 | ± 7.1 | 15 ± 8 | 16 ± 4 | 17 ± 5 | ± 0.90 | ± 4.0 | ± 1.07 | ± 3.2 | 11 ± 16 | 10.5 | 9.43 | 86.9 |
| KAR2 N 100% | 2 ± 1 | 8.14 | ± 0.42 | 7.64 | ± 0.45 | 75.6 | 10.9 | ± 0.36 | ± 2.6 | ± 0.82 | ± 5.0 | 8 ± 6 | 11.0 | 6.29 | 91.5 | 5 ± 6 | 11.6 | 84.9 | 11.1 | 86.0 |
| KAR3 N 100% | 15 ± 19 | 6.28 | ± 0.57 | 5.26 | ± 1.99 | 89.3 | 10.4 | ± 0.28 | ± 2.1 | ± 0.57 | ± 4.1 | 4 ± 3 | 6 ± 4 | 25 ± 8 | ± 0.39 | ± 2.9 | ± 0.67 | ± 5.3 | 14 ± 8 | 9.74 | 8.73 | 86.1 |
| KAR4 N 100% | 0 ± 3 | 7.59 | ± 0.71 | 7.55 | ± 0.71 | 82.3 | 9.26 | ± 0.51 | ± 4.2 | ± 0.60 | ± 5.6 | 3 ± 4 | 6 ± 10 | 19 ± 10 | ± 0.64 | ± 3.5 | ± 1.24 | ± 4.6 | 20 ± 11 | 10.7 | 8.75 | 93.3 |
| KAR5 N 100% | 6 ± 4 | 7.88 | ± 0.69 | 7.89 | ± 0.79 | 83.2 | 9.70 | ± 0.52 | ± 3.4 | ± 1.75 | ± 6.8 | 20 ± 11 | 16 ± 8 | 24 ± 6 | ± 0.4 | ± 2.8 | ± 1.19 | ± 3.2 | 35 ± 13 | 11.5 | 7.48 | 96.3 |

Note: Detriment is time difference between peak fist velocity and target contact; %stretch = | (FIN - SJC) | / arm length x 100% for punches and %stretch = | (AIC - HJC) | / leg length x 100% for the kick ($4.5.3$)
Similarly to TKD, to examine the group average data, the detriments, velocities and stretches were normalised and averaged. Detriments were normalised by dividing them by the execution time of the technique; and velocities and stretches were normalised by dividing the values per subject by the highest value obtained for that subject for that particular kick (table 6.9).

Table 6.9: Karate averaged normalised detriments, velocities and stretches, and average component timings for all subjects and both execution modes

<table>
<thead>
<tr>
<th></th>
<th>P1 normal</th>
<th>P1 100%</th>
<th>P2 normal</th>
<th>P2 100%</th>
<th>Kk normal</th>
<th>Kk 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalised detriment (%)</td>
<td>3.23</td>
<td>2.67</td>
<td>3.20</td>
<td>4.30</td>
<td>3.65</td>
<td>3.49</td>
</tr>
<tr>
<td>actual detriment (s)</td>
<td>0.009</td>
<td>0.008</td>
<td>0.010</td>
<td>0.013</td>
<td>0.019</td>
<td>0.017</td>
</tr>
<tr>
<td>component skill duration (s)</td>
<td>0.279</td>
<td>0.286</td>
<td>0.308</td>
<td>0.292</td>
<td>0.626</td>
<td>0.606</td>
</tr>
<tr>
<td>normalised peak velocity (%)</td>
<td>84.0</td>
<td>91.5</td>
<td>89.5</td>
<td>95.1</td>
<td>88.6</td>
<td>95.5</td>
</tr>
<tr>
<td>normalised contact velocity (%)</td>
<td>78.9</td>
<td>87.3</td>
<td>82.1</td>
<td>80.8</td>
<td>81.5</td>
<td>85.5</td>
</tr>
<tr>
<td>stretch at contact (%)</td>
<td>79.6</td>
<td>77.8</td>
<td>83.9</td>
<td>86.4</td>
<td>89.1</td>
<td>90.0</td>
</tr>
</tbody>
</table>

6.3.3. Target acquisition results

Tables 6.10 and 6.11 shows the results of the regressions for target pad readout and target marker acceleration for the karate subjects (§4.5.4). Using this regression data, the hits for punch 2 and the kick were qualified as being accurate or not, where 'accurate' was defined as lying within the 95% confidence level of the regression line.

Table 6.10: Regression of target pad readout against target pad marker acceleration for kicks from karate subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>R Square</th>
<th>Standard Error</th>
<th>Significance</th>
<th>Coefficient</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>0.67</td>
<td>0.328</td>
<td>1.18E-06</td>
<td>0.000400</td>
<td>0.000276</td>
<td>0.000523</td>
</tr>
<tr>
<td>KAR2</td>
<td>0.86</td>
<td>0.279</td>
<td>3.64E-09</td>
<td>0.000345</td>
<td>0.000277</td>
<td>0.000413</td>
</tr>
<tr>
<td>KAR3</td>
<td>0.83</td>
<td>0.329</td>
<td>6.46E-09</td>
<td>0.000497</td>
<td>0.000392</td>
<td>0.000602</td>
</tr>
<tr>
<td>KAR4</td>
<td>0.83</td>
<td>0.213</td>
<td>1.75E-08</td>
<td>0.000404</td>
<td>0.000316</td>
<td>0.000492</td>
</tr>
<tr>
<td>KAR5</td>
<td>0.84</td>
<td>0.335</td>
<td>7.79E-09</td>
<td>0.000578</td>
<td>0.000458</td>
<td>0.000698</td>
</tr>
</tbody>
</table>

157
Table 6.11: Regression of target pad readout against target pad marker acceleration for punches from karate subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>R Square</th>
<th>Standard Error</th>
<th>Significance</th>
<th>Coefficient</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>0.60</td>
<td>0.147</td>
<td>2.09E-03</td>
<td>0.000661</td>
<td>0.000373</td>
<td>0.00095</td>
</tr>
<tr>
<td>KAR2</td>
<td>0.69</td>
<td>0.149</td>
<td>9.56E-03</td>
<td>0.000493</td>
<td>0.000265</td>
<td>0.000722</td>
</tr>
<tr>
<td>KAR3</td>
<td>0.66</td>
<td>0.298</td>
<td>8.64E-06</td>
<td>0.000691</td>
<td>0.000455</td>
<td>0.000927</td>
</tr>
<tr>
<td>KAR4</td>
<td>0.83</td>
<td>0.191</td>
<td>1.60E-08</td>
<td>0.000639</td>
<td>0.000500</td>
<td>0.000778</td>
</tr>
<tr>
<td>KAR5</td>
<td>0.76</td>
<td>0.183</td>
<td>1.76E-06</td>
<td>0.000694</td>
<td>0.000494</td>
<td>0.000895</td>
</tr>
</tbody>
</table>

To determine whether the accuracy of the techniques changed between execution modes table 6.12 shows the percentage of punches and kicks that fell within, below or above 95% confidence levels of each subject’s regression.

Table 6.12: Percentage of punches 2 and kicks within, below and above the 95% confidence level of the subject specific regressions between pad readout and pad marker acceleration for normal and 100% mode of execution for kick 2 and kick 3 (no data for punch 1 is available as these kicks were aimed at the same pad as the kick)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Technique</th>
<th>Mode</th>
<th>Total number of tech's</th>
<th>% within</th>
<th>% below</th>
<th>% above</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>P2</td>
<td>Normal</td>
<td>8</td>
<td>25.0</td>
<td>37.5</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>8</td>
<td>22.2</td>
<td>44.4</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>Normal</td>
<td>12</td>
<td>50.0</td>
<td>33.3</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>11</td>
<td>54.5</td>
<td>27.3</td>
<td>18.2</td>
</tr>
<tr>
<td>KAR2</td>
<td>P2</td>
<td>Normal</td>
<td>7</td>
<td>71.4</td>
<td>14.3</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>5</td>
<td>40.0</td>
<td>40.0</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>Normal</td>
<td>10</td>
<td>60.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>20.0</td>
<td>30.0</td>
<td>50.0</td>
</tr>
<tr>
<td>KAR3</td>
<td>P2</td>
<td>Normal</td>
<td>10</td>
<td>80.0</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>0.0</td>
<td>20.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>Normal</td>
<td>10</td>
<td>20.0</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>30.0</td>
<td>10.0</td>
<td>60.0</td>
</tr>
<tr>
<td>KAR4</td>
<td>P2</td>
<td>Normal</td>
<td>10</td>
<td>40.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>30.0</td>
<td>20.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>Normal</td>
<td>10</td>
<td>10.0</td>
<td>40.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>20.0</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td>KAR5</td>
<td>P2</td>
<td>Normal</td>
<td>9</td>
<td>22.2</td>
<td>33.3</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>9</td>
<td>33.3</td>
<td>22.2</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>Normal</td>
<td>10</td>
<td>50.0</td>
<td>30.0</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>10</td>
<td>20.0</td>
<td>30.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

It is important to examine whether the accurate hits in 100% mode were harder hits than in normal mode. Table 6.13 shows the average pad readouts for data points within the 95% confidence level of the regression line for separate kicks. Statistically significant differences are indicated with *. As these are two completely different techniques, it made no sense to group them and reanalyse the pad data as done for TKD results.
Table 6.13: Target pad readout for accurate punches and kicks (mean ± standard deviation) (* is significant)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Techn.</th>
<th>Normal mode pad readout</th>
<th>100% mode pad readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>P2</td>
<td>0.24 ± 0.20</td>
<td>0.13 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>0.45 ± 0.28</td>
<td>0.30 ± 0.17</td>
</tr>
<tr>
<td>KAR2</td>
<td>P2</td>
<td>0.19 ± 0.14</td>
<td>0.18 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>0.52 ± 0.27 *</td>
<td>1.17 ± 0.22 *</td>
</tr>
<tr>
<td>KAR3</td>
<td>P2</td>
<td>0.48 ± 0.11</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>0.78 ± 0.42</td>
<td>0.64 ± 0.50</td>
</tr>
<tr>
<td>KAR4</td>
<td>P2</td>
<td>0.52 ± 0.21</td>
<td>0.43 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>0.62</td>
<td>0.80 ± 0.28</td>
</tr>
<tr>
<td>KAR5</td>
<td>P2</td>
<td>0.21 ± 0.01</td>
<td>0.35 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>Kk</td>
<td>1.16 ± 0.43</td>
<td>0.69 ± 0.49</td>
</tr>
</tbody>
</table>

6.3.4. Kinematics 3 - Joint angles at target contact comparison results

Tables 6.14 to 6.16 describe the differences in joint angles at target contact between techniques executed in normal and 100% mode. Entries were included for statistically significant changes (S) and for kinematical differences (K) (§4.4.5). The first entry pertains to the y axis, the second to the x axis and the third to the z axis (§4.4.3; Appendix 2 for axes definitions).

The total number of statistically or kinematically significant angle differences is also shown for each subject. This total included information from greyed areas of the table which pertain to non-adjacent central segment angle changes (§4.5.5).

For the punches the table first displays data for the upper limbs starting with the punching arm followed by data on the central segments and finally data for the lower limbs starting with the front leg. For the kick, data on the kicking leg are followed by the non-kicking leg, the central segments, and lastly data on the upper limbs are presented starting with the front arm.
Table 6.14a: Significant (S) and kinematic (K) angle differences for the arms and trunk in 100% mode compared to normal mode for karate punch 1 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Shoulder</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ S Abduction</td>
<td>↑ S Abduction</td>
<td></td>
<td>↑ S Abduction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ S External Rotation</td>
<td></td>
<td></td>
<td></td>
<td>↑ S Internal Rotation</td>
</tr>
<tr>
<td><strong>Left Elbow</strong></td>
<td></td>
<td></td>
<td>↑ K Flexion</td>
<td></td>
<td>↑ K Flexion</td>
</tr>
<tr>
<td><strong>Right Shoulder</strong></td>
<td></td>
<td></td>
<td>↑ S Abduction</td>
<td>↑ S Abduction</td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td><strong>Right Elbow</strong></td>
<td>↓ S Varus Rotation</td>
<td></td>
<td>↑ S Flexion</td>
<td>↑ S Varus Rotation</td>
<td>↓ S Varus Rotation</td>
</tr>
<tr>
<td></td>
<td>↓ S Internal Rotation</td>
<td></td>
<td>↑ S Varus Rotation</td>
<td>↑ S Internal Rotation</td>
<td></td>
</tr>
<tr>
<td><strong>Head-Trunk</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Head – Upper Back</strong></td>
<td></td>
<td>↑ S Extension</td>
<td></td>
<td>↑ S Left Flexion</td>
<td>↑ S Left Flexion</td>
</tr>
<tr>
<td></td>
<td>↓ S CW Rotation</td>
<td></td>
<td></td>
<td>↓ S Left Flexion</td>
<td></td>
</tr>
<tr>
<td><strong>Upper back – Lower back</strong></td>
<td></td>
<td>↑ S Forward Flexion</td>
<td></td>
<td>↑ S Right Flexion</td>
<td>↑ S Forward Flexion</td>
</tr>
<tr>
<td><strong>Lower back – Pelvis</strong></td>
<td></td>
<td>↑ S Right Flexion</td>
<td></td>
<td>↑ S Right Flexion</td>
<td>↑ S Backw. Extension</td>
</tr>
<tr>
<td></td>
<td>↓ K Right Flexion</td>
<td></td>
<td></td>
<td>↓ S Backw. Extension</td>
<td></td>
</tr>
<tr>
<td><strong>Upper back – Pelvis</strong></td>
<td></td>
<td>↑ S Left Flexion</td>
<td>↓ S Right Flexion</td>
<td>↑ S Right Flexion</td>
<td>↓ S Backward Extension</td>
</tr>
<tr>
<td><strong>Pelvis-Trunk</strong></td>
<td>↑ S Right Flexion</td>
<td>↓ S Right Flexion</td>
<td></td>
<td>↑ S Right Flexion</td>
<td>↓ S Right Flexion</td>
</tr>
</tbody>
</table>
Table 6.14b: Significant (S) and kinematic (K) angle differences for the legs body in 100% mode compared to normal mode for karate punch 1 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↑ S Abduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ S Flexion</td>
</tr>
<tr>
<td>↑ S External Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>↓ S Varus → Valgus Rot.</td>
<td>↑ S Flexion</td>
<td>↑ S Valgus Rotation</td>
<td>↑ S Valgus Rotation</td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td><strong>Left Ankle</strong></td>
<td>↑ S Flexion</td>
<td>↓ S Extension → Flexion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S Abduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>↓ S External Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Hip</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↑ S Flexion</td>
<td></td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td>↓ S Varus Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>↓ S External Rotation</td>
<td></td>
</tr>
<tr>
<td><strong>Right Ankle</strong></td>
<td>↑ S Abduction</td>
<td></td>
<td></td>
<td>↑ K Flexion</td>
<td></td>
</tr>
<tr>
<td>↑ S External Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Changes</strong></td>
<td>17</td>
<td>10</td>
<td>12</td>
<td>22</td>
<td>16</td>
</tr>
</tbody>
</table>
Table 6.15a: Significant (S) and kinematic (K) angle differences for the arms and trunk in 100% mode compared to normal mode for karate punch 2 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th></th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right Shoulder</strong></td>
<td>† S Abduction</td>
<td>† S Flexion</td>
<td>† S Abduction</td>
<td>† S Flexion</td>
<td>† S Flexion</td>
</tr>
<tr>
<td></td>
<td>† S External Rotation</td>
<td>† S Internal Rotation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Right Elbow</strong></td>
<td>† K Flexion</td>
<td>† S Valgus → Varus Rot</td>
<td>† S Internal Rotation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Shoulder</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Left Elbow</strong></td>
<td>† S Varus Rotation</td>
<td>† S Flexion</td>
<td>† S Flexion</td>
<td>† S Flexion</td>
<td>† S Flexion</td>
</tr>
<tr>
<td></td>
<td>† S Internal Rotation</td>
<td>† S Internal Rotation</td>
<td>† S Internal Rotation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Head-Trunk</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Head – Upper Back</strong></td>
<td>† S Backward Extension</td>
<td>† K Backward Extension</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
</tr>
<tr>
<td></td>
<td>† S aCW Rotation</td>
<td>† S aCW Rotation</td>
<td>† S CW→aCW Rotation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Upper back – Lower back</strong></td>
<td>† S Forward Flexion</td>
<td>† S Right Flexion</td>
<td>† S Left Flexion</td>
<td>† S Forward Flexion</td>
<td>† S Left Flexion</td>
</tr>
<tr>
<td></td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
</tr>
<tr>
<td><strong>Lower back – Pelvis</strong></td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
</tr>
<tr>
<td></td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
<td>† S CW Rotation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Upper back – Pelvis</strong></td>
<td>† S Left Flexion</td>
<td>† S Left Flexion</td>
<td>† S Left Flexion</td>
<td>† S Left Flexion</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pelvis-Trunk</strong></td>
<td>† S Forward Flexion</td>
<td>† S Left Flexion</td>
<td>† S Backward Extension</td>
<td>† S Backward Extension</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 6.15b: Significant (S) and kinematic (K) angle differences for the legs in 100% mode compared to normal mode for karate punch 2 (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Hip</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>↓ S</td>
</tr>
<tr>
<td>-</td>
<td>Int→Ext Rotation</td>
</tr>
<tr>
<td>-</td>
<td>↓ S Abduction</td>
</tr>
<tr>
<td>Left Knee</td>
<td></td>
</tr>
<tr>
<td>↓ S</td>
<td>Varus→Valgus Rot</td>
</tr>
<tr>
<td>-</td>
<td>↑ S Valgus Rotation</td>
</tr>
<tr>
<td>Left Ankle</td>
<td></td>
</tr>
<tr>
<td>↓ S</td>
<td>Abduct'n→Adduct'n</td>
</tr>
<tr>
<td>↓ S</td>
<td>Ext→Int Rotation</td>
</tr>
<tr>
<td>-</td>
<td>↑ S Abduction</td>
</tr>
<tr>
<td>-</td>
<td>↓ S External Rotation</td>
</tr>
<tr>
<td>Right Hip</td>
<td></td>
</tr>
<tr>
<td>↑ S</td>
<td>Extension</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right Knee</td>
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<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right Ankle</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>↓ S Internal Rotation</td>
</tr>
<tr>
<td>Total Changes</td>
<td>17</td>
</tr>
</tbody>
</table>
Table 6.16a: Significant (S) and kinematic (K) angle differences for the legs and trunk in 100% mode compared to normal mode for karate kick (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hip</strong></td>
<td></td>
<td>K Range of Flexion</td>
<td></td>
<td>↓ S Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S Abduction</td>
<td></td>
<td>↑ S Abduction</td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td><strong>Left Knee</strong></td>
<td></td>
<td>K Range of Flexion</td>
<td></td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>↑ S Extension</td>
<td>↑ S Extension</td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td><strong>Left Ankle</strong></td>
<td>↑ S Extension</td>
<td>↑ S Extension</td>
<td></td>
<td>↑ S Extension</td>
</tr>
<tr>
<td></td>
<td>↑ S Abduction</td>
<td>↑ S Abduction</td>
<td></td>
<td>↑ S Abduction</td>
</tr>
<tr>
<td></td>
<td>↑ S External Rotation</td>
<td>↑ S External Rotation</td>
<td></td>
<td>↑ S External Rotation</td>
</tr>
<tr>
<td><strong>Right Hip</strong></td>
<td>↑ S Flexion</td>
<td></td>
<td></td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S Abduction</td>
<td></td>
<td></td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S External Rotation</td>
<td>↑ S External Rotation</td>
<td></td>
<td>↑ S External Rotation</td>
</tr>
<tr>
<td><strong>Right Knee</strong></td>
<td>↑ S Flexion</td>
<td>↑ S Flexion</td>
<td></td>
<td>↑ S Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S Varus Rotation</td>
<td>↑ S Varus Rotation</td>
<td></td>
<td>↑ S Varus Rotation</td>
</tr>
<tr>
<td><strong>Right Ankle</strong></td>
<td></td>
<td>↑ S Internal Rotation</td>
<td>↑ K External Rotation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ S Left Flexion</td>
<td>↑ S CW Rotation</td>
<td>↑ S CW Rotation</td>
<td></td>
</tr>
<tr>
<td>Head – Upper Back</td>
<td>↑ S Left Flexion</td>
<td>↑ S Left Flexion</td>
<td>↑ S Backw. Extension</td>
<td>↑ S Backw. Extension</td>
</tr>
<tr>
<td></td>
<td>↑ S aCW Rotation</td>
<td>↑ S CW Rotation</td>
<td>↑ S Left Flexion</td>
<td>↑ S CW Rotation</td>
</tr>
<tr>
<td>Upper back – Lower back</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ K Forward Flexion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↑ S Left Flexion</td>
<td>↑ S Left Flexion</td>
<td>↑ S Backw. Extension</td>
<td>↑ S Backw. Extension</td>
</tr>
<tr>
<td>Lower back – Pelvis</td>
<td>↑ S Left Flexion</td>
<td>↑ S CW Rotation</td>
<td>↑ S Backw. Extension</td>
<td>↑ S Forward Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S aCW Rotation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper back – Pelvis</td>
<td>↑ S Left Flexion</td>
<td>↑ S Left Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Left Flexion</td>
</tr>
<tr>
<td>Pelvis-Trunk</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Left Flexion</td>
<td>↑ S Forward Flexion</td>
<td>↑ S Left Flexion</td>
</tr>
<tr>
<td></td>
<td>↑ S Backward Extension</td>
<td>↑ S Forward Flexion</td>
<td></td>
<td>↑ S aCW → CW Rotation</td>
</tr>
</tbody>
</table>
Table 6.16b: Significant (S) and kinematic (K) angle differences for the arms in 100% mode compared to normal mode for karate kick (↑ increase; ↓ decrease; CW clockwise; aCW anticlockwise). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Shoulder</strong></td>
<td></td>
<td>↓ S Flexion → Extension</td>
<td>↑ S Abduction</td>
<td>↓ S External Rotation</td>
<td>↓ S External Rotation</td>
</tr>
<tr>
<td>&amp; Abduction</td>
<td>↑ S</td>
<td>⇓ S External Rotation</td>
<td>↑ S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; External Rotation</td>
<td></td>
<td>⇓ S Flexion</td>
<td>↑ S</td>
<td></td>
<td>↓ S External Rotation</td>
</tr>
<tr>
<td><strong>Left Elbow</strong></td>
<td></td>
<td>↓ S Flexion</td>
<td>↑ S Flexion</td>
<td>↓ S Varus Rotation</td>
<td>↓ S Valgus Rotation</td>
</tr>
<tr>
<td>&amp; Valgus Rotation</td>
<td>↑ S</td>
<td>↓ S Flexion</td>
<td>↑ S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; Internal Rotation</td>
<td></td>
<td></td>
<td>↑ S</td>
<td></td>
<td>↓ S Varus Rotation</td>
</tr>
<tr>
<td><strong>Right Shoulder</strong></td>
<td></td>
<td>↓ S Flexion</td>
<td>↑ S Abduction</td>
<td>↓ S Abduction</td>
<td>↓ S Abduct'n→Adduct'n</td>
</tr>
<tr>
<td>&amp; Varus Rotation</td>
<td>↑ S</td>
<td></td>
<td>↑ S</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Right Elbow</strong></td>
<td></td>
<td>↓ S Flexion</td>
<td>↑ S</td>
<td></td>
<td>↓ S Varus Rotation</td>
</tr>
<tr>
<td>&amp; Varus Rotation</td>
<td></td>
<td></td>
<td>↑ S</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Changes</strong></td>
<td>21</td>
<td>28</td>
<td>18</td>
<td>20</td>
<td>26</td>
</tr>
</tbody>
</table>
The tables above highlight a number of differences in the execution of the combination. To put these tables into context, the maximal standard deviations recorded for the joint angles in normal mode from all three contacts are given in table 6.17. As defined in §4.5.5, kinematic difference means that about three quarters of the 100% mode results lie outside ± one standard deviation from the average of the normal mode kinematics.

Table 6.17: Karate maximal standard deviations of contact joint angles for normal mode (for axis definitions see §4.4.3)

<table>
<thead>
<tr>
<th></th>
<th>Y (deg.)</th>
<th>X (deg.)</th>
<th>Z (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>19.0</td>
<td>5.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Knee</td>
<td>22.6</td>
<td>4.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Ankle</td>
<td>10.5</td>
<td>2.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Head – trunk</td>
<td>5.1</td>
<td>4.4</td>
<td>7.7</td>
</tr>
<tr>
<td>Head – upper back</td>
<td>7.4</td>
<td>6.2</td>
<td>10.6</td>
</tr>
<tr>
<td>Upper back – lower back</td>
<td>4.9</td>
<td>3.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Lower back – pelvis</td>
<td>4.3</td>
<td>4.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Upper back – pelvis</td>
<td>7.2</td>
<td>6.5</td>
<td>11.9</td>
</tr>
<tr>
<td>Pelvis – trunk</td>
<td>6.3</td>
<td>5.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Shoulder</td>
<td>19.0</td>
<td>16.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Elbow</td>
<td>22.1</td>
<td>4.3</td>
<td>16.0</td>
</tr>
</tbody>
</table>

The most commonly observed angle differences from tables 6.14-6.16 (i.e. at least three differences per joint axis) are described below. It is assumed that the athlete aimed to keep their head pointed towards the target in the description of longitudinal rotations of the back. Differences for individual joints are summarised below if at least three out of five subjects demonstrated a difference for that joint angle.
Punch I

Punch I closely resembles a front hand jab (fig. 6.1). The main difference between this punch and a classical jab is that the subject actively pushes forward into the opponent’s space rather than remaining on the spot. The greatest joint angle differences between modes were seen in the legs and in the central segments if non-adjacent segment angles were included. This, presumably, was mainly due to the short transfer time between completing punch 1 and commencing punch 2. When looking at the subjects as a group more contact joint angle differences were observed in this punch than in punch 2 (tables 6.14-6.15). Individual changes are summarised below.

Figure 6.1: Punch 1 contact

Punching shoulder: increased abduction 3/5

Non-punching shoulder: increased abduction 3/5
Non-punching elbow: decreased varus rotation 3/5

Upper back – lower back: increased right flexion 2/5; decreased right flexion 1/5
Lower back – pelvis: increased right flexion 2/5; decreased right flexion 1/5
Upper back – pelvis: decreased left flexion 1/5; increased right flexion 2/5;
Pelvis – trunk: increased right flexion 3/5; decreased right flexion 1/5
Front knee: increased flexion 3/5
increased valgus rotation 5/5
decreased internal rotation 3/5
Front ankle: decreased extension 2/5; increased flexion 1/5

Punch 2

This punch is thrown with the reverse hand whilst shuffling forward (fig. 6.2). This position needed to reduce the athlete’s momentum in preparation for the kick and appeared to be quite established within the combination. Most differences were observed in the central segments this time and the angles of the legs seemed to display very little changes as summarised below.

![Punch 2 contact](image-url)

Figure 6.2: Punch 2 contact

Punching shoulder: increased external rotation 1/5; increased internal rotation 2/5
Non-punching elbow: decreased flexion 3/5
Head – upper back: increased backward extension 3/5
Upper back – lower back: increased right flexion 1/5; increased left flexion 2/5
decreased CW rotation 3/5
Lower back – pelvis: decreased backward extension 4/5
Pelvis – trunk: decreased backward extension 2/5; increased forward flexion 1/5
Back knee: decreased internal rotation 3/5
Kick

The kick is executed to the head with the front leg after the athlete has stepped up (fig. 6.3). The body should be turned sideways to present as small a target as possible to the opponent. Sometimes the athlete may travel forward as the kick progresses, i.e. the standing leg skips forward as the kicking leg extends. The kick displayed the most changes for the group (table 6.16) as summarised below.

![Figure 6.3: Kick contact](image)

| Kicking ankle: | decreased extension 3/5 |
|               | increased abduction 4/5 |
|               | increased external rotation 4/5 |

| Non-kicking hip: | decreased external rotation 1/5; decreased internal rotation 3/5 |

| Non-kicking knee: | increased flexion 4/5 |
|                  | increased internal rotation 1/5; decreased internal rotation 2/5 |

| Head – trunk: | increased forward flexion 1/5; decreased forward flexion 3/5 |
|               | decreased left flexion 4/5 |
|               | decreased CW rotation 4/5 |

| Head – upper back: | decreased left flexion 3/5 |
|                   | increased aCW rotation 2/5; decreased CW rotation 3/5 |

| Upper back – lower back: | increased forward flexion 2/5; decreased forward flexion 1/5 |
Lower back - pelvis: decreased backward extension 3/5; increased forward flexion 1/5

Upper back – pelvis: increased forward flexion 4/5
decreased left flexion 3/5

Pelvis – trunk: increased forward flexion 3/5; decreased backward extension 1/5
decreased left flexion 3/5
decreased aCW rotation 3/5

Front shoulder: increased external rotation 1/5; decreased external rotation 3/5

Front elbow: decreased flexion 2/5; increased flexion 1/5
decreased valgus rotation 2/5; decreased varus rotation 1/5

Back shoulder: increased abduction 1/5; decreased abduction 2/5
6.4 Karate kinetic results

Reliable kinetic calculations could only be done if one or no feet are on the floor (§4.4.4). Data were scaled in time and normalised by body mass as described in §4.5.6.

6.4.1. Qualitative comparison of joint moments

Initially a qualitative inspection of the moment curves was conducted to identify any obvious similarities or differences between modes. Table 6.18 below shows the main differences between the moment curves for normal and 100% modes of execution for each subject (fig. 4.24 and 4.25). Entries were made for qualitatively noticeable differences in magnitudes of the moments, variability of the moments in magnitude and phasing of temporal characteristics between trials of the 100% execution of the kick. For all joints the moments after contact of the kick appeared to become quite varied between trials.

The table suggests that the moments about the X axis of the hip, i.e. abductor-adductor (§4.4.6) of the kicking leg were bigger in 100% mode. A lot of change in variability was seen in the supporting leg, where for some subjects curves improved in uniformity and for others they deteriorated. Moments of the neck and upper back also showed different changes in variability, deteriorating in timing or magnitude uniformity. For the upper limbs, moments appeared very noisy, which was to be expected as they were only small in magnitude.
Table 6.18: Qualitative description of differences of moment curves in 100% mode compared to normal mode for karate kick (↑ increase; ↓ decrease; M magnitude; t temporal characteristics; C target contact; neg negative; pos positive). For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Hip</td>
<td>↑ pos after C</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↓ M uniform @ / after C</td>
<td>↑ pos after C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>↑ M uniform @ / after C</td>
</tr>
<tr>
<td>Left Knee</td>
<td>↑ pos @ C</td>
<td>↑ pos after C</td>
<td>-</td>
<td>↑ t uniform @ / after C</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>↑ pos after C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Right Hip</td>
<td>↑ pos before C</td>
<td>↑ M uniform</td>
<td>-</td>
<td>↑ M uniform</td>
<td>↑ pos before C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>↑ M uniform</td>
<td>-</td>
<td>↑ M uniform</td>
<td>-</td>
</tr>
<tr>
<td>Right Knee</td>
<td>↑ M uniform</td>
<td>↑ neg after C</td>
<td>-</td>
<td>↑ neg before / @ C</td>
<td>↑ neg after C</td>
</tr>
<tr>
<td></td>
<td>↑ M uniform</td>
<td>↑ neg after C</td>
<td>-</td>
<td>↑ M uniform</td>
<td>↑ neg after C</td>
</tr>
<tr>
<td>TOPJC (neck)</td>
<td>↑ t uniform @ / after C</td>
<td>↑ t uniform @ / after C</td>
<td>-</td>
<td>↑ M uniform @ / after C</td>
<td>-</td>
</tr>
<tr>
<td>MIDJC (upper back)</td>
<td>↑ t/M uniform</td>
<td>↑ neg @ C</td>
<td>↑ M uniform @ C</td>
<td>-</td>
<td>↑ t uniform @ / after C</td>
</tr>
<tr>
<td>LOWJC (lower back)</td>
<td>-</td>
<td>-</td>
<td>↑ M uniform @ C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Front Shoulder</td>
<td>↑ M uniform</td>
<td>↑ t/M uniform</td>
<td>↑ pos @ C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>↑ M uniform</td>
<td>↑ t/M uniform</td>
<td>↑ pos @ C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Front Elbow</td>
<td>↑ M uniform</td>
<td>-</td>
<td>↑ M uniform</td>
<td>-</td>
<td>↑ pos before C</td>
</tr>
<tr>
<td>Back Shoulder</td>
<td>↑ M uniform after C</td>
<td>-</td>
<td>-</td>
<td>↓ M uniform</td>
<td>↓ pos @ C</td>
</tr>
<tr>
<td>Back Elbow</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: entries in the table refer to how moment curves for all trials in 100% mode differ from those in normal mode; see figures 4.22 and 4.23 for examples. For kinetic hierarchy and segments used to calculate moments at these joints refer to §4.4.4, figure 4.7 and table 4.4.
6.4.2. Quantitative variability in joint moments

To further illustrate these qualitative findings the moments for the kick were interpolated to a common time base and the standard deviation time histories were calculated and compared between execution modes (table 6.19). A moment curve with a statistically greater standard deviation (p ≤ 0.05) was assumed to be more variable. The variability of the moment throughout the duration of the kick was relevant as any observed kinematic differences at target contact may be due to moments that occur over a certain time period rather than at a given instant in time. For each joint there is a y, x and z entry in line with the angle definitions (§4.4.6 and §4.4.3).

Table 6.19: Execution mode with largest statistically significant difference in the standard deviations of the moment curves for karate kick. For each joint the first value pertains to the y axis, second to the x axis and third to the z axis (§4.4.6).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Axis</th>
<th>KAR1</th>
<th>KAR2</th>
<th>KAR3</th>
<th>KAR4</th>
<th>KAR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Hip</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Left</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Knee</td>
<td>x</td>
<td>100%</td>
<td>normal</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Non-kicking Leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Hip</td>
<td>x</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
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<td>100%</td>
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<td>100%</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Right</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Knee</td>
<td>x</td>
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<td>100%</td>
</tr>
<tr>
<td></td>
<td>z</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Trunk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIDJC</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
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</tr>
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<td></td>
<td>z</td>
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<td>100%</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>LOWJC</td>
<td>y</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>-</td>
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<tr>
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</tbody>
</table>

The above table shows that generally the moment curves of the 100% mode of execution showed more variability than those of the normal mode. The same trends were
also observed when analysing the variability up to target contact and from target contact separately. The average moment time histories for each kick were not significantly different between execution modes.

6.4.3. Joint moments of the kicking leg

To compare the magnitude of these joint moments between subjects and with the literature the average peak hip extensor moments and average peak knee flexor moments of the kicking leg were calculated (table 6.20). These normalised values corresponded to hip extensor moments ranging from 45 Nm to 103 Nm and knee flexor moments ranging from 40 to 65 Nm.

Table 6.20: Average normalised peak moments (Nm/kg) and absolute ranges of average peak moments (Nm) of the kicking leg for karate athletes for both modes of execution

<table>
<thead>
<tr>
<th>Subject</th>
<th>Execution mode</th>
<th>Hip Extensor Moment (Nm/kg)</th>
<th>Knee Flexor Moment (Nm/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAR1</td>
<td>Normal</td>
<td>0.83</td>
<td>0.62</td>
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<td>0.67</td>
<td>0.61</td>
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<td>KAR2</td>
<td>Normal</td>
<td>0.78</td>
<td>0.84</td>
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<td>1.00</td>
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<tr>
<td>KAR3</td>
<td>Normal</td>
<td>1.39</td>
<td>0.85</td>
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<td></td>
<td>100%</td>
<td>1.12</td>
<td>0.78</td>
</tr>
<tr>
<td>KAR5</td>
<td>Normal</td>
<td>1.17</td>
<td>0.87</td>
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<td></td>
<td>100%</td>
<td>0.93</td>
<td>0.55</td>
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<tr>
<td>Absolute Range (Nm)</td>
<td>45 – 103 Nm</td>
<td>40 – 65 Nm</td>
<td></td>
</tr>
</tbody>
</table>

6.4.4. Generic kinetic observations

The kick appeared to display proximal distal sequencing (§2.2.9) of the moments of the kicking leg for all subjects: the hip extensor peak occurred before kick contact and the knee flexor peak occurred on kick contact (fig. 6.4). This is similar to previous research which recorded both peaks shortly before target contact (Robertson et al., 2004).
Figure 6.4: Sequencing of peak hip extensor moment (A) and peak knee flexor moment (B) for karate. The hip peak occurs before target contact and the knee peak occurs after target contact (contact is at 1 relative time; left curve is for normal mode and right curve is for 100% mode)

Generally, variability increased in 100% mode. Moments of both legs showed the least variability for all subjects in either execution mode. Little or no variability was observed in abductor-adductor and flexor-extensor moments of the kicking hip in either mode; more was observed in longitudinal rotator moments. Similarly, little variation was observed for valgus-varus and flexor-extensor moments of the kicking knee up to contact. For the non-kicking leg, all subjects displayed very little variability up to kick contact in abductor-adductor moments of the hip; more was observed in flexor-extensor and longitudinal rotator moments throughout the kick. For the non-kicking knee, little variability was seen in valgus-varus and flexor-extensor moments leading up to contact, although in 100% mode there was more variability after contact. The longitudinal rotator
moment of the neck appeared to demonstrate a relatively large variability when compared to other moments of the neck and the variability tended to increase in 100% mode. The same was observed in the upper back. Moments in all directions of the upper and lower back appeared quite varied with flexor-extensor moments in the lower back becoming quite variable after kick contact. For all central segments the magnitudes of the moments changed in 100% mode. Moments of the arm were generally reproducible in both modes although moments about the frontal and longitudinal axes of the joints appeared noisy and tended to also show relatively large variability. These moments and their variability were small in magnitude and were most likely due to errors caused by short frontal and transverse axes and consequently were not commented upon.

6.4.5. Variability in joint moment histories

To gain a better understanding of where in the moment time histories the locus of variability lies, the average moment and standard deviation curves of both modes were plotted. These are presented for certain cases in figures 6.5-6.27 where the y axis intersects the x axis at kick contact which is at 1 MT2 (§4.5.6). The complete set of average moment curves for all subjects, joints and execution modes is given in Appendix 6.

These figures show that the overall moment-time profiles tended to be similar between execution modes. Sometimes peak amplitudes were noticeably higher in the 100% mode (e.g. fig. 6.9). The width of the standard deviation bands tended to be bigger in 100% mode which supports the statistical analysis of the variability (table 6.19). The curves showing the least and the most marked changes between modes of executions for each subject are presented below.

KAR1

For this subject least variability was seen in moments of the front shoulder (fig. 6.5). Quite interestingly the moments of the kicking hip showed a marked increase in variability (fig. 6.6). The kicking knee also displayed an increase in flexor variability (fig.6.7). The supporting leg also displayed large increases in variability of the hip (fig. 6.8).

KAR2

Very little variability was shown in all moments of the kicking leg although abductor and valgus peaks were higher in 100% (fig. 6.9). The knee flexor moment of the kicking
leg showed a reduction in variability just after contact (fig. 6.10). There was a marked
difference between modes in magnitudes in lateral moments of the lower back leading up
to and at contact (fig. 6.11). A similar observation was made for the upper back (fig. 6.12).
In both cases less variability was observed in 100% mode, particularly after contact. The
varus moment of the standing knee showed a marked increase (fig. 6.13). In this subject
the variability in the central segments remained consistent between execution modes.
Figure 6.5: KAR1 K front shoulder flexor-extensor moments

Figure 6.6: KAR1 K kicking hip moments

Figure 6.7: KAR1 K kicking knee flexor-extensor moments

Figure 6.8: KAR1 K non-kicking hip moments

a. flexor-extensor

b. abductor-adductor
Figure 6.9: KAR2 K kicking leg abductor-adductor and valgus-varus moments

Figure 6.10: KAR2 K kicking knee flexor-extensor moments

Figure 6.11: KAR2 K lower back lateral moments

Figure 6.12: KAR2 K upper back lateral moments

Figure 6.13: KAR2 K non-kicking knee varus moments

a. hip

b. knee

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Moments of both the kicking leg and non-kicking leg showed least variability although certain moments showed a very large increase of variability after contact (fig. 6.14, 6.15). Lateral moments of the central segments showed magnitude changes around contact particularly for the neck and lower back (fig. 6.16). The neck also displayed marked amplitude increases of peaks in longitudinal rotation before contact (fig. 6.17).

Generally speaking the variabilities for the kicking leg and non-kicking leg appeared the smallest (fig. 6.18) although the longitudinal rotator moment of the kicking hip showed wide variability in both modes (fig. 6.19). The flexor moment of the kicking knee also showed increased variability after kick contact (fig. 6.20). In the central segments most notable changes were in lateral direction. The lateral moment of the neck showed a reduction in variability in 100% mode (fig. 6.21). This was also true for the upper back moments leading up to kick contact (fig. 6.22). The lateral moments of the lower back became more variable and the shape of the curve changed markedly (fig. 6.23).

This subject displayed least variability in the upper back although amplitudes seemed to decrease in 100% mode (fig. 6.24). A decrease in variability around contact could be seen in the lateral moments of the lower back (fig. 6.25). Interesting changes could be seen in the flexor-extensor moments of the kicking leg even though earlier results showed that the variability for the whole kick (table 6.19) was comparable (fig. 6.26). The abductor peak of the kicking hip was higher in 100% mode. The lateral moments of the neck increased in amplitude (fig. 6.27).
Figure 6.14: KAR3 K kicking leg abductor-adductor and valgus-varus moments

Figure 6.15: KAR3 K non-kicking knee flexor moments

Figure 6.16: KAR3 K central segments lateral moments

Figure 6.17: KAR3 K neck longitudinal moments

a. hip

b. knee

a. neck

b. lower back
Figure 6.24: KAR5 K upper back moments

a. forward-backward flexor-extensor

b. lateral flexor

Figure 6.25: KAR5 K lower back lateral moments

Figure 6.26: KAR5 K kicking leg flexor-extensor moments

a. hip

b. knee

Figure 6.27: KAR5 K neck lateral moments
6.5 Karate approximate entropy

The approximate entropy (ApEn) (Pincus, 1991) was calculated for all unfiltered joint angle time histories throughout each technique (§4.5.7). This value gave an indication of how ordered the signal, in this case the joint angles, was for the duration of a trial. If the signal was highly ordered the ApEn will be close to 0; the more chaotic the signal the higher the ApEn value. The average ApEn value for each joint axis was compared between execution modes. The general ranges of the calculated ApEn for each technique and body section are shown in table 6.21.

Table 6.21: Ranges of approximate entropy averages for all joint angles for all karate trials (§4.5.7) (calculated with run length 2 and filter length 0.5)

<table>
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<th></th>
<th>Legs</th>
<th>Central segments</th>
<th>Arms</th>
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</thead>
<tbody>
<tr>
<td>Punch 1</td>
<td>0.03 – 0.46</td>
<td>0.04 – 0.41</td>
<td>0.06 – 0.49</td>
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<tr>
<td>Punch 2</td>
<td>0.05 – 0.52</td>
<td>0.09 – 0.53</td>
<td>0.04 – 0.51</td>
</tr>
<tr>
<td>Kick</td>
<td>0.08 – 0.46</td>
<td>0.09 – 0.47</td>
<td>0.05 – 0.51</td>
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</table>

When comparing the ApEn for both execution modes they were generally comparable for each joint axis. A comparison of ApEn values between execution modes is given in table 6.22, which gives the mode with significantly higher ApEn (p ≤ 0.05). The first entry pertains to the y axis, the second to the x axis and the third to the z axis (§4.4.3; Appendix 2 for axes definitions).
Table 6.22a: Performance mode with significantly higher approximate entropy of joint angle time histories (p ≤ 0.05) for the legs and trunk for karate athletes (norm = normal mode; 100% = 100% mode)

<table>
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Table 6.22b: Performance mode with significantly higher approximate entropy of joint angle time histories for the arms for karate athletes (norm = normal mode; 100% = 100% mode)

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Chapter 7

DISCUSSION

7.1 Chapter outline

This chapter addresses the main concepts of the previous chapters. Firstly, a generic biomechanical discussion is presented. Secondly, the research questions are redressed in light of the results in chapters 5 and 6. Thirdly, a general discussion of the study is given with particular reference to motor control and the limitations of this study. Fourthly, recommendations for future studies into research of whole-body movement and skill reproduction following on from this work are explored. Lastly, the main conclusions of this research are presented.

7.2 Biomechanics

7.2.1. Biomechanical tools

Previous studies looking at the variability of skill reproduction examined the kinematics of individual techniques (Philips, 1985; Sforza et al. 2000; Sforza et al., 2001; Sforza et al., 2002). This study was more elaborate as it investigated multiple techniques executed as parts of martial arts combinations, and examined the change in variability of these combinations with different execution modes. This was achieved, by firstly looking at differences in the kinematics, and secondly by exploring the variability of the kinetics (Young & Marteniuk, 1995) in order to uncover possible causes for the observed differences and gain an insight into motor control of the martial arts movements. Additionally, the findings of the study provided information for training and developing these skills (Zatsiorsky & Fortney, 1993).

Established complex biomechanical methods such as 3D movement analysis, JC approximation and segment definitions, were used together with whole-body analysis as a basis for this research. In order to produce relevant information about the studied martial arts combinations, a 3D fourteen-segment representation of the body was created in which all segments were defined as independently as possible and four central segments were considered to represent the spine (§4.4.2 and §4.4.3). This model included subject specific
inertial information (§3.7 and §4.4.5). Functionally determined JCs were used for the shoulders and the hips in addition to predictive equivalents allowing for two different sets of joint angles of the limbs to be included in the analysis (§4.4.2, §4.4.7, §4.4.8, Appendix 2).

7.2.2. Kinematic and kinetic output

The kinematic and kinetic output from the model were comparable to values found in the literature for movements similar to the techniques used in the martial arts combinations of this study. Kicking velocities for comparable kicks range from 7-11 m/s (Feld et al., 1979; Béraud & Gahéry, 1995; §2.2.7). For TKD, the peak foot velocities recorded for the slide front foot turning kick were 8.5-12.4 m/s; for the back leg turning kick 11.0-14.1 m/s and for the jumping turning kick 10.2-13.4 m/s when executed on the target pads. The foot velocities for the karate kick were 9.2-11.6 m/s. On the heavy bag, the peak velocities increased to 14.7-15.9 m/s for the TKD jumping turning kick which was higher than any of the speeds in the reviewed literature. For karate, the front hand jabbing punch reached peak fist velocities of 5.3-8.7 m/s, and the reverse punch 8.8-11.0 m/s. The literature reports fist velocities for a range of punches of 6-14 m/s (Walker, 1975; Blum, 1977; Feld et al., 1979; Smith & Hamill, 1985; §2.2.8).

The peak moments for the kicking leg recorded in this study were also comparable to those in the literature. For karate, the average peak hip extensor moments were 45-103 Nm and the average peak knee flexor moments were 40-65 Nm. For TKD the values were kick-dependent. For kick 1, average peak hip extensor moments were 89-200 Nm and average peak knee flexor moments were 54-117 Nm. For kick 2, average peak hip extensor moments were 155-351 Nm and average peak knee flexor moments were 95-151 Nm. For kick 3, average peak hip extensor moments were 88-142 Nm and average peak knee flexor moments were 45-83 Nm. Representative values from the literature were a peak hip extensor moment of 110-180 Nm and a peak knee flexor moment of 70-135 Nm for rugby punting (Kerwin & Hamilton, 1987); a peak hip extensor moment of approximately 375 Nm and a peak knee flexor moment of approximately 160 Nm for a high martial arts front kick (Sørensen et al., 1996); and a peak hip extensor moment of approximately 380 Nm and a peak knee flexor moment of approximately 125 Nm for a karate front kick (Robertson et al., 2004). Two scenarios became apparent for the occurrence of the peaks: they either occurred at the same time as reported by Kerwin & Hamilton (1987) for rugby punts, and by Sørensen et al. (1996) and Robertson et al. (2004).
for martial arts front kicks, or the hip peak slightly preceded the knee peak as previously reported by Roberts et al. (1974) and Luhtanen (1988) for ball kicking. The knee peak never preceded the hip peak in this study as reported by Putnam (1983, 1991, 1993).

7.2.3. **Measurement error limitation**

Despite the fact that kinematic and kinetic results from this study are comparable to those from the literature, the data obtained will contain a degree of error. Within the scope of this study of complex 3D whole-body movement, precautions were taken to ensure that errors were kept as low as possible. The motion capture system was calibrated several times until a low reconstruction error (§4.2) was achieved; gaps in marker trajectories were filled using carefully considered steps (§4.3.2); markers of the dynamic trial were attached to bony landmarks (§3.4); and filter settings were chosen in such a way that marker position data were smoothed without oversmoothing impacts or movement reversals (§4.3.3). JCs were based on at least two different definitions so differences in joint angles at target contact could be obtained from two different sources (§4.4.2, §4.4.7, §4.4.8, Appendix 2).

Even with these considerations, a certain degree of error in marker reconstruction and position is unavoidable, due to a skin movement artefact introduced during athletic movement (§2.3.1 and §2.3.2). Therefore, segment orientations and JC locations, and subsequently joint angles, will be affected. Additionally, these positional errors will have affected the kinetics in two ways. Firstly, the positions of the CoM of each segment will have a systematic error in location related to the kinematics, and secondly, second derivatives used to calculate joint moments will have an enhanced systematic error (Challis & Kerwin, 1996). These errors are expected to have been of a magnitude typical to 3D motion capture experiments, and results from this study were indeed comparable to those of previous studies. There were, however, limitations to this study which are elaborated upon in §7.8.
7.3 Research question 1

Q1: 'Does skill execution by individual elite martial athletes differ when executed under competition maximum (100% mode) compared to training maximum (normal mode), and if so to what extent?'

This question is addressed for TKD first and for karate second. Three main areas were examined, namely (1) durations and distances of total body movement, (2) velocities, timing and stretch of the striking limb, and (3) kinematic joint angle differences at target contact. These three contacts were considered to be attractor states where the martial athlete will aim to minimise final positional variance (Harris & Wolpert, 1998).

7.3.1. TKD whole body movement

When executing the combination in 100% mode one would expect the TKD athletes to be faster. Moving faster generally means to cover the same or more distance in less time. This is not necessarily how the athletes interpret 'moving faster' as they may just aim to produce the individual kicks in less time, i.e. the kicking action itself is faster. However, simply executing the kicks in less time does not necessarily imply that the average execution speed of the combination increases, i.e. the athlete is approaching the opponent faster. Reducing the time of a kicking action may mean that less distance can be covered and thus could potentially lower the approach velocity. The average speed for the whole body was obtained by measuring the durations and the distances of the individual techniques and the combination. As can be seen from table 5.4, most subjects increased the average effective speed of the combination and of individual techniques, however this was not always achieved in the same way.

The duration of a kick primarily depends on two parameters: firstly, the time taken to kick and return the leg to the floor (kicking time), and secondly, the time required to cover the ground to the target (travel time). The durations for the combinations improved significantly (by 50 to 80 ms) or were maintained (table 5.2); however, athletes were unable to improve the execution times for kick 1. Improved average speeds for kick 1 were achieved by significant improvements in distance (table 5.3) in the same time (table 5.2), indicating that athletes may have opted to exert more effort to move forward further, hence producing more power and consequently more work, rather than lowering the kicking time. TKD4 maintained average speed for kick 1 although more distance was
covered and hence produced similar power pushing forward but possibly had a large kicking time.

Significant improvements in duration were observed for kick 2 and kick 3 in four subjects (table 5.2), but these were not accompanied by significant changes in distance for kick 2 and only one significant increase for kick 3 (table 5.3). Hence improvements in average speed were mainly due to improved kicking times without any additional effort for moving further. The only significant increases in execution distance of individual techniques were observed for kick 1 and kick 3 (TKD2 and TKD5). TKD2 improved both these distances, and the effective and total execution distances (§4.5.2) also improved significantly. TKD5 only improved kick 1 and the effective distance. Hence, it seems that once enough drive had been generated with kick 1, the athlete then focuses on improving the time for lifting, kicking and lowering the leg rather than push forward harder. For the athletes that demonstrated a non-significant improvement in effective distance there appeared to be a trade-off in covered distance between kicks: TKD3 increased distances for kicks 1 and 3 but the distance for kick 2 decreased, yet all average speeds increased; TKD4 showed a large increase in distance for kick 1 maintaining average speed but covered less distance for the remaining kicks resulting in a higher average speed.

TKD4 only manages to cover more distance in kick 1 but requires significantly more time (70 ms more). If the duration of kick 2 and kick 3, and thus the total combination, are lowered at the expense of the duration of kick 1, this may become detrimental in competition as a longer time for the opponent to recognise cues (Mori et al., 2002) is created. All subjects completed kick 1 in a shorter time (0.49-0.59 s) than the 700 ms reported in the literature (Hong et al., 2000).

TKD1 had lower speeds and distances for all parts and the effective and total combination, even though most durations were decreased significantly. Hence, in 100% mode, it would seem that executing the combination in less time was more important for this subject than increasing its overall speed as distance was sacrificed for a quicker execution.

In conclusion, two main changes were observed when athletes performed the kicking combination in 100% mode. The most common difference was that more power was generated in kick 1 so that more distance could be covered in the same time. With this greater momentum, the athletes focussed on lowering the kicking time of subsequent kicks rather than trying to cover more ground in less time. In one subject there also appeared to be an extra ‘drive’ forward for the last kick.
A different change was observed for one subject who simply performed all parts and the total combination in less time. For this subject the main focus was to simply reduce the kicking time. Subjects were asked to perform the combinations in 100% mode in such a way that scoring in a minimum amount of time was absolutely imperative. Provided that the athlete is in range, reducing the kicking time only would give the opponent less time to react. However, coupling the first kick with an extra push forward, and therefore a higher approach velocity, also means that the opponent may be overran and thus off balance. Firing the subsequent two kicks in less time would therefore make scoring more likely as not only does the opponent have to react quickly, but has to do so from a disadvantageous body position.

7.3.2. TKD measurements of the kicking leg

When kicking in 100% mode, one may expect the TKD athlete to produce the kicking action with more effort and thus reach higher peak foot velocities. However, this extra effort may go to waste if the timing of the kick deteriorates, i.e. the target is reached at higher RoM values where the anatomical constraints cause the kick to decelerate more. In order to investigate how the athletes may have changed these aspects of the kicks in 100% mode, differences in characteristics of the kicking leg such as detriments, peak and contact velocities, and stretch (table 5.5) are discussed.

When comparing execution modes, the only significant differences were observed for kick 2 and kick 3. TKD2 increased the contact velocity for kick 2 by raising the peak velocity, implying that hitting the target harder is mainly done by faster kicks, not by improving the timing, i.e. reducing the detriment, of the kick (table 5.5). However, when the contact velocity decreased significantly, as demonstrated by TKD1, this was due to a significant increase in detriment and therefore stretch (table 5.5). TKD5 demonstrated a significant increase in contact stretch without any significant changes in the contact velocity, which may indicate that the velocity does not change much between these high stretch values (table 5.5).

In kick 3, TKD1 showed a significant rise in contact velocity which may have been caused by the combined improvements of peak velocity and contact stretch, even though they were not significant (table 5.5). TKD2 managed to produce a significantly higher peak velocity at a higher stretch, and at the same time lower the detriment without significant effect on the contact values yet the contact velocity improved markedly (by approximately 3 m/s) (table 5.5).
Generally, contact velocities for kick 2 in 100% mode were lower with larger stretch values than in normal mode due to increased detriments as there was little change in the peak velocities. Where lower contact velocities in kick 3 were observed, they tended to be due to a combination of changes in detriment and peak velocity. The results also suggested that the TKD athletes were able to produce peak or near-peak velocities at higher stretch values than the 70 to 80% suggested by Atha et al. (1985).

Hitting the target with higher contact velocity is favourable as a knock-down or knock-out is more likely, which can lead to an extra point or a win (§1.2.1). The data indicate that in both modes detriments were predominantly positive, i.e. the foot was already decelerating on target contact. This may indicate that some factor was preventing the athletes from impacting the target maximally. The question arose whether the athletes were not producing a maximal kick, even in 100% mode, due to the nature of the targets they were kicking. The light target pads did not offer much resistance and kicking them at full speed may lead to hyperextension and possible injury of the knee (Robertson et al., 2004). The athletes may therefore have timed the kick in such a way that they could control the knee extension. Data obtained from the kicks executed on the heavy bag implied that athletes will kick harder with zero or negative detriments, if they know the target will offer enough resistance to slow down the knee extension, thus allowing target impact with maximal deformation (Pieter & Pieter, 1995). Although kinetic information was not available for the trials with the heavy bag as the substantial force applied to the bag could not be quantified, the peak knee flexor moment (see Q2 below and §5.4.3) was expected to be lower (Robertson et al., 2004) and future studies using an adequately instrumented heavy bag may confirm this.

This observation has direct relevance to competition training as the technique's execution, and therefore quite possibly its codification and initiation, may be quite different in competition compared to using the target pads. Given that scoring is continuous, athletes may benefit from producing a maximal kick to knock-down or knock-out the opponent (§1.2.1), but evidently do not attempt to do this when training with the pads. This will be addressed in more detail for Q4.

In conclusion, if contact velocities increased this was generally achieved by increasing peak velocities. Lower contact velocities were due to increased detriments and lower peak velocities. Generally athletes produced peak velocities that were close to maximum in both modes. Athletes are not optimising the timing of a kick for maximal
impact as the foot is already decelerating at target contact which is most likely the result of kicking a target that does not offer adequate resistance.

7.3.3. *TKD accuracy and impact force*

So far it has been indicated that executing the combination in 100% mode led to athletes: pushing forward more for certain parts of the combination; reducing the times taken to lift and lower the kicking leg; and producing stronger contractions to kick faster. All these changes may have an effect on the accuracy of the kicks and on the delivery force of these techniques.

Comments on impact force could only be made for accurate hits to the centre of the pad as this is where the force transducer was positioned. Although high and low hits could be identified and excluded (§4.5.4), the data available did not allow for laterally inaccurate hits to be excluded in this way.

Pad readout data were only available for kick 2 and kick 3, as kick 1 and kick 3 hit the same target. It was assumed that the readout of this pad related to kick 3, as this kick generally landed with a higher contact velocity. However, it is worth noting that if kick 3 did not hit the centre of the pad (§4.5.4) it is possible that if kick 1 was more accurate and was produced with sufficient velocity, that the readout pertained to this kick instead.

Little information could be obtained from the target pads on how the accuracy or impact force changed between execution modes. The data were not conclusive on whether subjects became more accurate or kicked harder in 100% mode. Some subjects produced a larger number of accurate kicks for one kick whilst deteriorating for the other; other subjects improved or deteriorated for both, and one subject remained the same for both. Based on the limited number of accurate kicks three subjects hit less hard and two hit harder in 100% mode. A discussion of how these data relate to the linear speed-accuracy trade-off (SATO) and the impulse-variability theories is presented in §7.7.3.

7.3.4. *TKD joint angle differences at target contact*

Although athletes move differently in each trial as outlined in §1.3 and §2.2.1-§2.2.2 (Bernstein, 1967; Latash, 1998; Schmidt & Lee, 1999), it can be expected that the athletes aim to minimise positional variance at target contact (Harris & Wolpert, 1998). This suggests that joint angles at target contact should demonstrate relatively little variability. Nonetheless, as athletes are aiming to kick in less time, producing faster movements in a number of body parts, and continue movements after contact is made, this may affect the
configuration of the body and hence joint angle variability at target contact. When comparing joint angles at target contact between modes, a number of differences were observed.

The joint angles at contact suggested that for kick 1 in 100% mode (table 5.12) athletes may not have lifted the kicking leg as much as in normal mode, indicated by less hip abduction. This hip also tended to be more flexed. For all athletes, the head seemed to be tilted further back in 100% mode. As the forward flexion of other central segments increased, not changing the head angle would have meant the head would no longer be pointed at the opponent (fig. 7.1).

The extra forward flexion in the trunk may be a consequence of the extra momentum created in 100% mode in kick 1. Ensuring the body remains as forward as possible, keeps the body’s CoM further forward than in normal mode and may therefore assist the combination to progress more easily and the momentum to be carried through to the next section. Additionally, more effective mass is committed to the kick which therefore may impact the target harder.

Figure 7.1: Adjustment of head position in TKD kick 1 in 100% mode due to increased forward flexion of central segments. The dashed lines represent the segment configurations of the back in normal mode and the solid lines represent the segment orientations in 100% mode. As angles a and b decrease (more forward flexion), angle c will demonstrate more backward extension of the head to keep the eye line constant.

The central segments in kick 1 seemed to have completed less longitudinal rotation in relation to the segment above them, and the longitudinal rotation of the head was adjusted
accordingly to keep the opponent in sight. When examining the individual trunk segments, it would seem that the reduction in longitudinal rotation happened in two main areas, between the neck and the upper back, and between the pelvis and the lower back. TKD3, on the other hand, showed increased CW rotation of the pelvis in relation to the lower back indicating that lower sections of the spine have not reduced their rotations in the same way as the segments above them. Changes in lateral rotation were also observed but were different for different subjects.

In kick 2 (table 5.13), the wide range of knee flexion angles at contact adds further support to the earlier observation that athletes are reaching for the target as already noted based on high stretches and low contact velocities (table 5.5 and §7.3.2). Increased extension of the non-kicking ankle indicated a push either forward or upward indicating that the take-off phase for kick 3 was initiated earlier. This may mean the athlete is trying to reduce the transfer time between techniques in 100% mode. The most noticeable changes in the central sections were those in longitudinal rotation. Angles in the upper regions of the back indicated less longitudinal rotation in the direction of the kick. Angles related to the lower regions indicated that these have rotated more towards the kick than in normal mode, meaning that for most subjects more rotation occurred in the lower sections of the trunk in 100% mode, i.e. the kicking side of the pelvis was brought forward more, whilst the remaining trunk sections rotated as per normal mode. To progress to kick 3 from kick 2, a reduction in upper body rotation for kick 2 presumably assists the initiation of kick 3. Yet, athletes cannot sacrifice the forward rotation of the pelvis as they are reaching further for this kick in 100% mode.

Interestingly, TKD2, who was the only subject to produce significantly higher peak and contact velocities for kick 2, also showed different longitudinal rotations. The lower sections of the trunk were further back compared to normal mode and it may be that this 'keeping back' of the pelvis may have allowed a faster foot contact velocity to be generated. For the other subjects the increased rotation of the pelvis may have resulted in a body position where this was not possible.

 Generally, angles between the lower back and the pelvis showed more left flexion indicating the upper body is leaning left more. This may be a postural adjustment to cope with the higher stretch values that were observed for this kick.

In kick 3, very few differences in contact joint angles were seen in the kicking leg. In contrast a number of differences were observed for the non-kicking leg, including more hip abduction and more knee flexion, which was expected as the leg was in the landing phase,
for most subjects. It is likely that landing had progressed to a different degree when the foot contacted the target pad, especially when the person was moving faster and therefore also likely to jump less high.

There appeared to be increased left flexion of the head for all subjects, i.e. the left shoulder came up towards the head more. This was coupled with increased left flexion for other central segments indicating more lean into the kick, thus ensuring that the CoM comes forward more. Differences in forward flexion of the head varied. If changes were observed for the longitudinal rotation of central segments they mostly involved less rotation of the lower back sections. Less pelvis rotation in 100% mode again suggests a change in segmental sequencing, i.e. segments were not rotating with respect to each other as they were in normal mode. Additionally, in some cases more rotation of the upper back section was observed.

In conclusion, for each kick, few differences in angles of the kicking leg at target contact occurred between modes. In kick 1, these were related to the hip and ankle, and in kick 2 to the knee. The reduced hip abduction will be caused by the athlete reducing the amount of time used to lift the kicking leg. Lifting the leg using the abductor muscles is relatively intensive and the athlete may perceive this as a slow action, and thus sacrifice the degree of abduction to reduce the kicking time. The decreased extension of the ankle can be explained by the athlete paying less attention to kicking foot position in 100% mode. The ranges of knee angles observed for the knee in kick 2 are due to the high stretches.

Longitudinal rotations of the whole trunk were reduced in 100% mode (Roosen & Pain, 2007a) and in kick 2 and kick 3 some subjects appeared to have a larger offset between the rotation of the lower and upper parts. This difference in longitudinal rotation in 100% mode is likely to be related to athletes producing individual kicks in less time and reducing transfer time between kicks and also appears to be kick-specific. Further support for the athlete aiming to cut down the transfer time between techniques comes from the increased forward flexion of back segments in kick 1 and the increased left flexion in kick 3 as both actions bring the CoM forward in the direction of the combination, and from the earlier initiation of the take-off phase between kick 2 and kick 3 in 100% mode. The forward projection of the CoM also results in more effective mass being committed to the technique which may result in a harder impact. Provided that these angle differences did not adversely affect the distance covered in a technique, they will have improved its average speed as they resulted in a lower execution time.
7.3.5. Karate whole body movement

As with TKD athletes, one would expect the karate athletes to be faster in 100% mode, but the interpretation of faster may again be different for different techniques (§7.3.1). Athletes may simply produce a punch or kick in less time, i.e. the striking action itself is faster, rather then ensuring the body as a whole is moving faster, and thus limiting the distance that can be covered during a technique. For karate athletes, two average movement speeds were defined based on the distances covered by the hips and the shoulders. All subjects improved the effective average speeds of the combination based on these distances. Generally, there were more significant increases in upper body (shoulders) average speed than in lower body (hips) average speed (tables 6.6 and 6.7).

The duration of a punch or kick depends on the punching or kicking time, and the time to cover the ground to the target. The retraction of the limbs does not contribute as the arm is retracted together with the extension of the next punch, and time is only recorded until kick contact. The durations of the karate combination either reduced significantly (by 70 ms) or remained approximately unchanged (table 6.2). The total execution time was only significantly lowered if the time of punch 2 and the kick were lowered. Athletes were unable to significantly lower the execution times of both punches together. Three athletes significantly lowered the execution time of punch 2, and one subject lowered the execution time for punch 1. Four athletes significantly lowered the execution time of the kick. KAR3 performed all techniques in the same time in both modes.

Improved average speeds for punch 1 were primarily achieved by significant improvements in distance (tables 6.3 and 6.4). However, the improvements in distance for this punch were predominantly observed at the shoulder, with two significant increases and three non-significant increases. There was only one significant increase at hip level and two non-significant increases. This means that two subjects covered less distance at the hip and hence covered less ground but projected the upper body forward more. Data from table 6.5 supports this observation as generally the shoulders are further ahead of the hips in 100% mode for this punch.

No significant increases in duration were observed for punch 1 although KAR5 needed 30 ms extra in 100% mode indicating that karate athletes limit its execution time. Improving the average speed of this punch by covering more distance in more time may not be a good tactic as a longer execution time may present more cues to an opponent (Mori et al., 2002), which in karate could be even more detrimental than in TKD due to the
intermittent scoring (§1.2.2). It may be more beneficial to execute punch 1 in the same or less time and present fewer cues, giving the opponent less time to react and possibly catching them by surprise thus allowing more time for the subsequent punch (Jessop & Pain, 2004), which appears to be the strategy employed by the majority of subjects. Only KAR2 simultaneously lowers the execution time and increases distance for this punch.

Significant reductions in duration were observed for punch 2 (table 6.2), but these were generally not accompanied by significantly improved distances at either hip (table 6.3) or shoulder level (table 6.4). In fact, KAR4 demonstrated a significant decrease in distance covered at shoulder level. Hence improvements in average speed for this punch were mainly due to improved punching times for KAR1 and KAR5. Interestingly, KAR3 demonstrated a significant increase in average velocity even though the execution time remained the same and only non-significant increases in distance were observed. It seems that for this subject, the improvement was due to increased distance and hence higher power production.

Improvements in average speed for the kick were mainly due to a lower execution time (table 6.2) as most subjects do not demonstrate a significant change in distance (tables 6.3 and 6.4). Only two subjects also show an increased execution distance. KAR1 covered more distance based on the hips and KAR3 covered more distance based on the hips and the shoulders. These two subjects therefore also produced more power to push forward in the kick.

In conclusion, athletes were able to cover more distance with a greater average velocity, thus improving the execution of the combination, which was mostly due to the change in execution of punch 2 and the kick. Movement speeds for techniques were improved in 100% mode using different strategies. The most common difference was that more power was generated in punch 1 so that more distance could be covered in the same time. For some subjects this increased distance is for the upper body only. One subject lowered the execution time for this punch and also demonstrated increased upper body projection. The average speed of punch 2 was improved in one of two ways. Three subjects did so mainly by lowering the punching time, whilst one subject increased distances, i.e. this subject ‘drove’ harder into the punch. For the kick, which could result in a high score (§2.2.2), three strategies were observed. Most subjects significantly lowered the execution time only, indicating that the reduction of the kicking time was most important. One subject lowered execution time coupled with an improvement in distance, indicating that as well as kicking in less time, more power was created to move towards the
target. One subject did not change the execution time but covered more distance. Generally subjects aimed to drive the opponent further back with punch 1 and generate an adequate momentum to be able to execute punch 2 and the kick in less time.

7.3.6. Karate measurements of the punching arm and kicking leg

Significant increases in peak velocities of the punching hand and kicking foot were observed in all three techniques (table 6.8): in punch 1, for three subjects (KAR3, KAR4 and KAR5), in punch 2 for all subjects but KAR2 who punched the fastest, and in the kick for all subjects with additional significant decreases in detriment and increases in stretch at peak velocity.

In punch 1, contact velocity was improved significantly by increasing the peak velocity alone (KAR4) or together with a significant decrease in detriment (KAR5). Although significant increases in peak velocities were observed in punch 2, no changes were observed in contact velocity, presumably due to the increase in stretch at target contact.

Interestingly, in the kick, significantly higher peak velocities could occur at significantly higher stretches (KAR2, KAR3 and KAR4) and led to increased contact velocities, which in one case was also coupled with a decreased detriment (KAR3). This may indicate that there is an optimal stretch at which to maximise peak velocities. The stretches were all similar to the optimal range of 70-80% quoted in the literature (Atha et al., 1985). In one case a significantly higher peak velocity was cancelled out by a rise in detriment (KAR5), and subsequently a significantly higher contact stretch, as no changes in contact velocity were observed.

Comparing contact velocities of all three techniques, although the kicks tend to contact with a velocity comparable to that of punch 2, the punch had more effective mass behind it (tables 6.5 and 6.7). Punch 1 tended to have a lower contact velocity than the other techniques and, as the athlete did not drop the body into punch 1 as much as in punch 2, was likely to carry less effective mass (compare fig. 6.1 and 6.2). More discussion on how energy transfer may be controlled by karate athletes is given in §7.7.5.

Data for the group demonstrated punch 1 to have the lowest detriment and the lowest velocities (tables 6.8 and 6.9). These punches were likely to have a low detriment to make them less easy to block given that their absolute contact velocities were low. A low velocity will also cause less elbow strain if overstretched and therefore large detriments may not be required. In 100% mode, the athletes increased contact velocity of the fist in
punch 1 without a change in detriment. The detriment in punch 2 was larger and increased slightly in 100% mode resulting in larger stretches and slightly lower contact velocities.

In conclusion, significant increases in peak fist or foot velocity were observed for all techniques in 100% mode, but mostly for the kick. These increases caused significantly higher contact velocities for punch 1 and the kick only. For both punch 1 and the kick there was one case where increased contact velocity was the result of both decreased detriment and increased peak velocity. The contact velocity for punch 2 dropped due to higher stretch values at contact. The largest detriments were observed in the kick. These observations are likely to be related. As more momentum was generated with punch 1, the opponent is likely to have moved back further. This then necessitates the higher observed stretch for punch 2, to ensure the opponent keeps moving back. The relatively high detriments observed for the kick may imply that, as the opponent is still moving backwards, the kick is timed carefully in order to hit the retreating target.

7.3.7. Karate accuracy and impact force

In karate a controlled contact to the head is crucial (§1.2.2) and hence it is important to check whether the accuracy and impact force with the target have changed as a consequence of the faster movements in 100% mode. Similar to TKD, punch 1 and the kick hit the same pad. However, the contact velocities were always markedly higher for the kick and hence the target pad readout was assumed to relate to the kick, even if the contact was not quite central (§4.5.4).

Generally, given the assumptions of the analysis (§4.5.4) and the number of accurate techniques, inferring trends from these target pad data requires caution. As with TKD, little information could be gained from the target pad data on how the accuracy or impact force of the techniques changed between execution modes. Only one subject produced a greater number of accurate hits for punch 2 in 100% mode which were harder than the accurate hits in normal mode. The remainder of the subjects produced fewer accurate hits, which were all softer than in normal mode. For the kick the differences in the number of accurate kicks and impact force between execution modes were quite varied. Two subjects increased the impact force of the kick, one of which did so significantly, but all others decreased it. It was important for the kick to land with 'touch control' and hence a reduction in impact force in 100% mode is not unexpected – this trade-off may have contributed to the observed variability. The body punch may be delivered with more impact hence a softer contact may actually lead to a missed scoring opportunity. This may
indicate that this punch may be used to keep the opponent on the back foot and position them for the high-scoring kick rather than used to score. A discussion of how these data relate to the linear SATO and the impulse-variability theories is presented in §7.7.3.

7.3.8. Karate joint angle differences at target contact

As with the TKD athletes, karate athletes, even though they move differently each time as outlined in §1.3 and §2.2.1 §2.2.2 (Bernstein, 1967; Latash, 1998; Schmidt & Lee, 1999), are expected to have limited positional variance at target contact (Harris & Wolpert, 1998). This suggests that the variability in joint angles at target contact should similarly be minimised. However, as athletes produce punches and kicks in less time, are exhibiting faster movements in a number of body parts, and continue to move after contact with the target is made, this may affect body configuration at target contact.

In punch I (table 6.14), the punching shoulder was more abducted in 100% mode indicating protraction of the scapula and reaching forward with the punch (fig. 7.2). The main observations for the non-punching arm were increased shoulder abduction and decreased varus rotation of the lower arm. Varied angle differences in lateral flexion were observed in all back segments at target contact. The longitudinal rotation of the upper trunk indicated that it may have turned more towards the direction of the punch, i.e. the left shoulder was brought forward more in 100% mode and the upper body was reaching for the target (fig. 7.2). This indirectly supports the observation that some subjects increase forward lean towards the target (table 6.5). For the front leg most changes were seen at the knee, possibly representing extra loading in 100% mode, and may indicate that a later stage in the transfer between both punches was reached at the time of contact with the target, i.e. the athlete may be aiming to cut down the transfer time between punch 1 and punch 2.

Figure 7.2: Reaching with the shoulder in karate punch I in 100% mode. The extra abduction measure in 100% mode at the shoulder (a) is indicative of more shoulder protraction (b) to reach for the target.
In punch 2 (table 6.15), the differences in longitudinal rotation of the upper punching arm at target contact were varied, which may indicate that the fist was not turned over into the punch consistently. For two subjects increased abduction indicating the protraction of the scapula was observed again. The elbow of the non-punching arm was more flexed, which may indicate that at time of contact of punch 2 the punching arm from punch 1 had been retracted further. The head was tilted back further in 100% which may be a result of greater momentum coming forward resulting from extra drive observed in punch 1 especially at the shoulder level (table 6.7). The longitudinal rotation of trunk segments seemed to indicate that for some subjects the phasing of sequential rotation of trunk segments (Van Gheluwe & Van Schandevijl, 1983) may have changed between execution modes. Generally less rotation towards the punch occurred in 100% mode, presumably in order to not have to rotate these sections back as much when the kick was initiated, thus saving transfer time.

For all subjects most differences in contact joint angles were observed for the kick (table 6.16). These differences mostly manifested themselves in the central segments. Most subjects showed a significant decrease in ankle extension of the kicking foot indicating they may have paid less attention to the foot position at kick contact during 100% mode as the ankle should be fully extended to hit the target with the instep. Subjects tended to show differences in longitudinal rotation of the hip and knee of the support leg indicative of more outward rotation. This extra rotation of the leg may be linked with angle differences for central segments. All subjects showed less left flexion of the central segments, which indicated the body leaned less into the kick, causing the CoM to be further back. The extra rotation of the standing leg thus pointing the foot backwards more would offer more support for the increased lean away from the kick (fig. 7.3). Similarly to TKD, the head was generally back further whilst other central segments displayed more forward flexion, i.e. more arching of the spine.
Figure 7.3: Trunk and support leg positions for the karate kick in 100% mode. The leg has rotated outward more (a) to add support for the increased back lean (b).

The knee of the non-kicking leg was flexed more in 100% mode. The longitudinal rotation of the trunk and upper back about the head showed less longitudinal rotation toward the kick for all subjects in 100% mode. Similarly, the angles of the pelvis and trunk seemed to indicate less rotation between them. For some subjects (KAR1 and KAR2) the lower sections of the spine completed more rotation toward the kick in relation to the upper sections which may indicate that a certain degree of dissociation occurred, as was observed in TKD for kick 2 (§7.3.4). This may indicate that a certain amount of longitudinal rotation of the pelvis towards the target is required to deliver the kick, but the upper body is kept less rotated possibly to save time or to reduce the effective mass committed to the kick (fig. 7.4).

Figure 7.4: Difference in longitudinal rotations of trunk segments in the karate kick in 100% mode. The increased CW rotation observed at the pelvis is related to the decreased CW rotation of upper trunk segments.

In conclusion, angle data for punch 1 indicated that the upper body was used to gain extra distance to the target as demonstrated by the extra shoulder abduction of the punching arm and the increased longitudinal rotation of the punching side of the upper
body towards the target. The extra flexion of the front knee seemed to indicate that it was loaded more and in a later stage of the transfer phase between punch 1 and punch 2. In punch 2, the longitudinal rotation of the punching arm was varied indicating that less attention may be paid to the fist being fully turned over at contact. Some subjects demonstrated increased shoulder abduction indicating extra reach for the target, but longitudinal rotation of central segments towards the punch were generally reduced presumably in order to initiate the kick earlier. The kick in 100% mode demonstrated less lean of the trunk toward the target, which was accompanied by more outward rotation of the supporting leg for added stability. It may be that this lean would not be so apparent if the kick is followed by a further technique, as it would be time consuming to bring the CoM forward. However, as it is the last technique of the combination and athletes aim to score with it, the back lean most likely serves to control the delivery of the kick to the head (§1.2.2 and §7.7.5). Lower sections of the spine completed more longitudinal rotation toward the kick relative to the upper segments, which probably indicates that the upper sections have not rotated as far to save time and/or commit less mass to the kick.

7.3.9. Summary

In answer to research question 1, the data have shown that the execution of the martial combinations is different between execution modes. As outlined in the respective paragraphs above, both TKD and karate athletes pushed forward more, mainly for the first technique of the combination, reduced the kicking and punching times and produced stronger contractions to deliver the kicks and punches faster. The majority of angle differences indicated that athletes cut short movements in order to produce the combination faster. Rotations of the central segments towards the opponent were reduced in 100% mode, and other angles of the trunk indicated that the CoM is adjusted specifically to the requirements of each sport. In TKD it was kept forward further, which in turn assisted a faster execution. For the karate kick it was kept back further to limit energy transfer to the opponent’s head. Similarly angles of the support legs in both sports indicated an earlier initiation of the subsequent technique.

It appears the athletes exerted more effort to propel the body forward to generate more approach velocity in 100% mode. This in turn may not allow for the complete rotation of central segments or athletes may find the complete rotations of central segments into the techniques too costly when execution time is crucial. Certain segments connected to the trunk cannot necessarily reduce their rotation if the target is to be hit, e.g. increased
shoulder protraction in punches and no reduction in longitudinal rotation of the pelvis for the kicks. Generally angle differences in 100% mode indicate that the athletes are limiting the movements of the body in such a way that the combination can be continued with minimum effort and time, and faster moving fists and feet can be retracted more easily.

7.4 Research question 2

Q2: ‘What are the biomechanical causes for any observed differences between these modes and do they give an insight into the control of the movements?’

Joint moments have been used in the past to gain an insight into the control of movements (Young & Marteniuk, 1995). Hence, to investigate the causes of the observed kinematic differences between execution modes, the joint moments leading up to and beyond target contact were studied. Moments before target contact were used to gain an insight into causes of angle differences at contact, whereas moments after contact were investigated in light of transferring from one technique to the next. Possible control methods are suggested and these are expanded on in §7.7.

It is important to bear in mind that moments could only be reported for a limited time, namely when no more than one foot was on the floor (§4.4.4). Hence, no information is available to quantify the initial conditions of the combination and conditions between techniques where both feet were on the floor. Moreover, for karate, no joint moment information is available for the largest part of the combination. The way an athlete initiates the combination may influence subsequent parts of its execution.

7.4.1. General comments on joint moments

Generally, average moment time histories were comparable (Appendix 6) and not significantly different between execution modes (§5.4.2. and §6.4.2), indicating that, if motor programs are used for the execution of these techniques, the same programs were used in each mode (Schmidt & Lee, 1999). However, the variability of these average moment time histories, i.e. the moment standard deviation time histories, was usually significantly higher in 100% mode (tables 5.19-5.20 and 6.19), indicating that the parameterisation in relation to phasing and force of the program may have varied more (§2.2.2). When separating standard deviation moment histories into two parts, up to and after contact, the variability was significantly higher in 100% mode for both parts.
Although the patterns of the moment curves were repeatable intra-subject, they were not necessarily the same when comparing inter-subject. It was however possible to identify certain trends between subjects.

For TKD and karate athletes, moments for all segments generally became more variable after kick contact (Appendix 6), indicating that, rather than the increase in variability just being a consequence from the impact, it denoted a transfer phase from one technique to the next, identified in previous studies as the end of one unit of action and the start of a new unit (Schneider & Schmidt, 1995; Schmidt & Lee, 1999; §2.2.2). As with other kicking studies (Roberts et al., 1974; Putnam, 1983; Luhtanen, 1988; Putnam, 1993; Putnam, 1991; Sørensen et al., 1996; Robertson et al., 2004) the kicking leg demonstrated moments which were stopping the kicking movement: a hip extensor moment and a knee flexor moment (§7.2.2). These peaks usually occurred together for kick 1 and kick 3 on target contact (Kerwin & Hamilton, 1987; Sørensen et al., 1996; Robertson et al., 2004), or demonstrated proximal-distal sequencing of moments (Roberts et al., 1974; Luhtanen, 1988), with the hip extensor peak on contact being followed by the knee flexor peak shortly after for kick 2. For the karate kick, proximal-distal sequencing of moments was also observed (§6.4.3): the hip extensor peak occurred before kick contact and the knee flexor peak occurred on kick contact, as previously reported in some studies (Roberts et al., 1974; Luhtanen, 1988).

It appears that the manifestation of a proximal-distal moment sequence may be related to the type of kick or its impact restrictions. If the hip is no longer moving, the knee extension may be easier to control as observed in karate. In kick 2 for TKD, a high stretch value is reached which means that the movement at the hip has stopped before that of the knee. How these observations relate to motor control of the kicks will be discussed in §7.7.5.

7.4.2. Joint moment comparison between kicks

Average moment and standard deviation time histories were calculated for all kicks (Appendix 6) and are discussed together firstly for the kicking leg, secondly for the non-kicking leg, and lastly for the central segments. The leg trajectories of the kick in the karate combination are most comparable to kick 1 of the TKD combination (fig. 7.5; §3.6).
The moments of the kicking leg showed little variability in general, which is not surprising as the actions of the kicking leg are ballistic (Zehr et al., 1997). However, certain observations could be made across kicks. The longitudinal rotator moment of the kicking hip demonstrated noticeably more variability than other moments at the hip for TKD kick 1 and the karate kick. In TKD kick 2 and the karate kick, the abductor-adductor and flexor-extensor moments of the kicking hip became quite varied after kick contact. In the TKD kick this was presumably due to the kicking leg, which had reached a high extension, more or less being dropped from that position as the pelvis rotates CW to bring the other hip forward for the last kick. In the karate kick the reasons are probably similar, as the leg is dropped after kick completion. Peak flexor moments of the kicking knee demonstrated more variability in 100% mode for TKD kick 2, TKD kick 3, and the karate kick, which may be related to increased peak foot velocities, which would have required stronger muscle contractions. The knee flexor moment to stop this faster kick may be more variable as higher forces are required and thus force variability may also be higher (Schmidt et al., 1979; Sherwood & Schmidt, 1980; Newell & Carlton, 1985; Sherwood, Schmidt & Walter, 1988; Ulrich & Wing, 1991; Carlton & Newell, 1993; Schmidt & Lee, 1999).

More moment variability can be observed for the non-kicking leg and mostly in kick 2 and kick 3 in TKD and the karate kick. For all three of these kicks the longitudinal rotator moment of the hip is quite variable around and after kick contact. This is not unexpected as the non-kicking hip is the main pivot point around which the pelvis is rotated in the direction of the target. This variability appears to become more pronounced in 100% mode presumably in reaction to the increased momentum that was generated.
In karate, the extra outward rotation that was observed at the hip may also be related to this moment being particularly variable in 100% mode. In TKD kick 3 and the karate kick, the hip flexor-extensor and abductor-adductor moments both were quite variable, which are similarly likely to be related to controlling movement of the central body segments about this joint.

Most variability is seen in moments of the central segments, although certain moment patterns in the trunk for certain kicks were well-defined. For TKD kick 1, TKD kick 3 and the karate kick, lateral moments of the upper and lower back were remarkably variable. For TKD kick 1, the pattern of the lateral flexor moment curves also appeared to change between execution modes. As can be seen in figure 7.5, these three round kicks have the upper body in a more side-on position than TKD kick 2, which shares more characteristics with a front kick. Hence, marked variability in the lateral moments is not expected in TKD kick 2. For the other kicks, the lateral rotation of the trunk is obviously an important factor for keeping sight of the opponent and move the body’s CoM in an appropriate way (§7.3.4 and §7.3.8). Variability of forward-backward flexor-extensor moments of the upper and lower back was apparent at and after target contact for all kicks, which presumably is related to maintaining an adequate trunk position.

Looking at the longitudinal moments of central segments, those for the neck were the most variable which is likely to be related to the angle differences in longitudinal rotation of back segments (tables 5.12-5.14 and 6.16) to keep sight of the opponent. In the TKD kicks, the longitudinal moments of the upper and lower back were remarkably consistent, not only between modes but also between subjects. Similar observations have been reported in pitching which involves trunk movements not dissimilar to those in this study (Hong et al., 2001). For the karate kick the longitudinal moments, particularly for the upper back displayed more variability, presumably because the karate athlete needs to control the rotation more in order not to transfer much energy into the target with the kick.

In conclusion, moments of the kicking leg are generally well defined with little variability, which is not surprising as the kicking action itself was ballistic (§2.2.2; Zehr et al., 1997; McGarry & Franks, 2003), and the movement was likely to be very well defined in the motor system. Where marked variability did occur, this was for longitudinal rotator and abductor-adductor moments of the hip, and flexor-extensor moments of the knee. More variability was observed in the non-kicking leg and was most prominent at the hip as this joint is most likely to have to adapt to movements of the body in relation to the 'grounded' leg. Most variability was observed for central segments. This was apparent in
forward-backward flexor-extensor moments of the upper and lower back for all kicks, and in lateral moments for all kicks (Hong et al., 2001) except TKD kick 2. These moments serve to keep the trunk in an adequate position for the kick. Longitudinal rotator moments of the upper and lower back were generally well-defined (Hong et al., 2001), especially for TKD kicks which do not require the athlete to stop the rotation and limit energy transfer into the target. In the period after kick contact, moments were more variable which may indicate the transition between the end of one motor program and the start of another (Schneider & Schmidt, 1995; Schmidt & Lee, 1999; §2.2.2). The implications of these observations are discussed in §7.6.

7.4.3. Relation between joint moments and joint angles

The ApEn of unfiltered joint angles (§5.5 and §6.5) for the individual techniques of the combination gives an estimate of their regularity. Comparing these values between execution modes showed that generally there were no differences (tables 5.24 and 6.22), suggesting that the regularity of the angle time histories was comparable for both modes for the duration of a technique. In TKD, where differences did occur this tended to be for kick 2 and to some extent kick 1, and for karate in punch 1 and to some extent in the kick. However, these data (tables 5.24 and 6.22) do not give any information about how different a joint angle was at target contact between modes, nor do they give any indication of how different the moments causing the angle time histories were. They merely demonstrate whether an angle time history was more robust in one mode or the other. Hence, even though the ApEn of the signals from both execution modes for a technique may be comparable, the values at a particular instant in time may be different.

For the kicks, both moment data and ApEn data were available, which allowed for a further comparison. Moments tended to be more variable in 100% mode (tables 5.19-5.21 and 6.19), i.e. the average moment standard deviation for a technique was significantly higher in 100% (§4.5.6), even though the trends of the curves were generally maintained (Appendix 6), whilst the ApEn of the joint angle time histories was similar in both execution modes (tables 5.25, 6.22). In order to ensure the variability seen in the moment data was not an artefact of additional noise introduced by second derivatives (Challis & Kerwin, 1996), the ApEn of the second derivatives of the raw angle data were also determined (§4.5.7), and generally no significant differences were found between the execution modes. This may indicate that there is a movement template for the produced
actions, and that any variations in the moments served to ensure the template was reproduced.

The data for observed angle differences at target contact in 100% mode (§5.3.6, §6.3.4) were re-examined with the relevant moment data leading up to kick contact (up to the vertical axis in the average moment time histories in Appendix 6). The following scenarios were distinguished: no angle change and no moment change; no angle change but a moment change; angle change and no moment change; and angle change and moment change. A change in moment may be a different pattern and/or magnitude, and/or variability leading up to kick contact.

Table 7.1: TKD kicks: relation between observed contact angle differences and moment changes up to contact between modes (angle differences include significant and kinematic differences)

<table>
<thead>
<tr>
<th>TKD</th>
<th>Angle difference</th>
<th>No angle difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment change</td>
<td>32 %</td>
<td>52 %</td>
</tr>
<tr>
<td>No moment change</td>
<td>4 %</td>
<td>12 %</td>
</tr>
</tbody>
</table>

Table 7.2: Karate kick: relation between observed contact angle differences and moment changes up to contact between modes (angle differences include significant and kinematic differences)

<table>
<thead>
<tr>
<th>Karate</th>
<th>Angle difference</th>
<th>No angle difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment change</td>
<td>41 %</td>
<td>47 %</td>
</tr>
<tr>
<td>No moment change</td>
<td>3 %</td>
<td>9 %</td>
</tr>
</tbody>
</table>

Tables 7.1 and 7.2 show that for both sports, in approximately 50% of cases there was no significant angle difference for the joint at contact, but a noticeable change in moment leading up to contact. This suggests that the moment was adjusted to keep the angle the same at kick contact. The second most common situation, accounting for 30-40% of cases, was an angle change accompanied by a moment change leading up to contact. Situations involving no moment change were rarely observed (approximately 10-15% of cases) and these data indirectly support the suggestion that moment variations serve to ensure a movement template is reproduced as the most common observation involved an apparent moment change without an angle change.

In future, it may be interesting to investigate whether adjusting the run- and filter lengths (§4.5.7) may affect the ApEn comparisons. Ideally, the ApEn of the joint moments
should also be calculated. This was not possible in this study as the software used to calculate the kinetics automatically smoothed the calculated moments by using data from eight frames before and after the current time-frame. In order to obtain information on the ApEn of the joint moments, software that calculates 3D kinetics from unfiltered kinematic data is required. This was beyond the scope of the current study.

The above observations do not explain why at target contact, angle differences were observed (see §6.3.4 and §5.3.4), since both ApEn data and joint moment time histories (repeatable patterns of moment curves) indicated that similar actions occurred in both modes.

A possible explanation could be a difference in initial conditions for a technique, such as different forces, long initial movements and recoveries. The kinematics for both sports showed that particularly during the first technique of the respective combinations the distances and velocities changed between execution modes, as athletes increased their momentum. The different conditions created during these early phases of the combination could have created a knock-on effect which instigated the observed changes at technique contact. Similarly, if the conditions during the transfer phases of one technique to the next vary, the execution of the subsequent technique will be affected. The inappropriate timing and sequencing of certain events leading up to a ‘critical moment’, in this study hitting the target, have been shown to play a major role in the successful reproduction of other skilled actions (Hore et al., 1996; Jegede et al., 2005).

A further consideration is that the moments are manifestations of forces, including those created by the muscles crossing the joint all with their own activation timings. The greater momentum in 100% mode was created by higher muscle forces and force production variability has been shown to increase linearly with force production magnitude up to 65 % of maximal force (Schmidt et al., 1979; Sherwood & Schmidt, 1980; Newell & Carlton, 1985; Schmidt & Lee, 1999) and decrease (Sherwood & Schmidt, 1980; Ulrich & Wing, 1991; Carlton & Newell, 1993; Schmidt & Lee, 1999) or increase at a lesser rate (Newell & Carlton, 1985; Sherwood, Schmidt & Walter, 1988; Ulrich & Wing, 1991; Carlton & Newell, 1993) for larger forces. This increased force production variability in 100% mode may have led to more variability in initial or transfer conditions in 100% mode.

The data indicated that the moment variability is greatest in the non-kicking leg and trunk, and increased in 100% mode. The magnitudes of these joint moments (e.g. 2-2.5 Nm/kg for the knee extensor peak; 1.5-2.5 Nm/kg forward-backward flexion-extension,
approx. 2 Nm/kg lateral flexion in the lower back) are likely to be around or above 65% of maximal force production (Forrester, 2006). Hence, these data seem to suggest that variability continues to increase with force production above 65% of maximal force, in support of earlier studies (Newell & Carlton, 1985; Sherwood, Schmidt & Walter, 1988; Ulrich & Wing, 1991; Carlton & Newell, 1993).

In conclusion, the ApEn of the unfiltered joint angle time histories and the moment time histories for a technique may indicate that similar actions were occurring in both modes. However, the moment variability in 100% mode was greater than that in normal mode. It is assumed that, since the skills were completed successfully, the roles of the moments of the trunk and supporting leg may be of a regulatory nature to compensate for any perceived errors in execution of the distal segment after one reaction time had passed (Schmidt & Lee, 1999), thus incorporating environmental (Schmidt & Lee, 1999) and mechanical (Brown & Loeb, 2000; Campbell & Kirkpatrick, 2001) feedback (§2.2.2). Hence, the observed moment variability may generally ensure that a movement, or motor program, is carried out faithfully in elite athletes. In less skilled performers, these same areas may demonstrate variability, which may lead to deterioration of the skill.

7.4.4 Summary

In order to answer this research question, the moments at the joints leading up to target contact were examined. Moments of the kicking leg were well defined with little variability, and as previously discussed very few angle differences were observed for the striking limb. More variability was observed in the non-kicking leg and central segments. Recalling the answer to research question 1, these were the areas in which most angle differences were observed, as athletes adjust movements of certain segments to facilitate the faster execution of techniques and the continuation of the combination. Motor control characteristic also became apparent when examining the moment data. Moment curves in both modes were repeatable indicating that movement patterns are well defined in the motor system which may reflect motor programs or strong attractor regions of a dynamical system. The noticeable increase in variability towards the end of a technique may indicate the end of such a program or region and the start of a new one.

Generally, moments became more varied in 100% mode, which in part is caused by the faster execution of the combinations and in part by the reductions and the control of the trunk rotations. The biggest increases in variability were observed in the support legs and the central segments. Linking this with the observation that the ApEn of the unfiltered
joint angle time histories and the moment time histories for a technique themselves demonstrated little or no difference between execution modes, suggests that variability in certain segments may be an essential ingredient for the correct reproduction of these skills. In elite athletes the observed variability in certain moments appears to play a role in controlling the outcome of the combination. As the ballistic parts of the technique only allow for very limited correction based on feedback, the main regulation of the technique must originate from segments that do not undergo a ballistic action, such as the trunk and support leg. The variability in these areas of the elite athlete demonstrates the freedom of the system to adjust to the execution of the techniques so that they are delivered adequately. In less skilful athletes, variability in these areas, if not yet controlled, may be the main source of skill breakdown. It would seem pertinent to restrict variability initially until performers are competent in performing the combination, as already typically done in martial arts training. With an established movement pattern in its place, however, the athlete should then be allowed to explore different solutions thus making positive use of the variability. This will ultimately allow an individual to perform a skill to the best of their ability and will have ensured that the system has synthesised a coping mechanism for likely perturbations in execution.
7.5 Research question 3

Q3: 'Are the causes for any differences in execution the same in all individuals?'

Data showed that subjects tended to change the execution in terms of duration, distance and average speed in 100% mode, and that these adaptations were not the same for all individuals. Hence, it would seem that causes for these adaptations are also different between subjects. As no moment data were available for movement onset, this study cannot comment further on how initial conditions changed between individuals.

The results indicated that if angle differences were observed between execution modes in the limb delivering the technique, these tended to be similar across subjects (§7.3.4 and §7.3.8). For the kicks, the kicking leg moments also appeared to be robust between execution modes (§7.4.2). More angle differences were observed in segments that were not directly involved in the delivery of the technique. Angle differences of central sections particularly, were not always the same between individuals, especially in lateral and longitudinal rotations (§7.3.4 and §7.3.8). Similarly, the moment variability differences were not always the same for central sections (§5.4.5, §6.4.5 and §7.4.2).

Given that the segments which were not directly involved in the delivery of the technique may assume a role related to movement correction and forward progression (§7.4.3), it was very likely that, even though differences may happen for similar reasons, i.e. coping with movement errors or perturbations (§2.2.2 and §2.2.3), the moments that caused the observed differences were subject-specific due to the individual masses and inertias and other individual movement characteristics involved. The data in this study do not provide further answers to this question. In order to address this question more fully, it may be required to record EMG data of muscles of the central segments and supporting limbs during the execution of the combination.
7.6 Research question 4

Q4: 'What recommendations can be made to martial athletes and their coaches based on the findings of this study?'

7.6.1. Recommendations for general skill enhancement

Apart from drilling these combinations, martial athletes typically undertake endurance and strength training. The primary focus of the strength training is the improvement of the striking actions themselves. Data from this study suggested that actions of the striking limbs were well-defined within the movement patterns of the combinations. This is testament to the volume of training for these actions. This study also showed that the joint moments of other segments displayed markedly more variability and suggested that during the striking actions in these skills these segments may have a regulating role in the execution to ensure that the striking limb remained on target.

Angle data for trunk segments suggested that the position of the upper body may vary between separate executions of the combination. For karate in particular, the high standard deviations observed in the forward and backward lean (table 6.5) indicated that a part of the movement reproduction is not well controlled which could lead to the athletes exposing areas for the opponent to counter. As the position of the upper body changed at each key stage of the combination from one execution to the next, subsequent parts may be affected such that corrections are needed to produce the combination fully.

Moments of the supporting leg could become quite variable during the execution of the kicks in these combinations. Additionally, angles for the front knee in the punches of the karate combination seemed to indicate additional loading in 100% mode.

It would seem pertinent therefore, in order to further improve the execution of these combinations, to dedicate training specifically to enhance the regulatory and stabilising roles of the trunk segments and of the non-striking limbs, so that the martial athlete is able to faithfully reproduce skills (Schmidt & Lee, 1999) and to ensure the muscles involved in such correcting actions are conditioned suitably to deal with likely perturbations. Inadequate conditioning could, given the high degree of variability, be a catalyst for injury (§7.6.2).

Most variability in the execution appeared to occur during the intermittent phases linking the techniques (Schneider & Schmidt, 1995; Schmidt & Lee, 1999; §2.2.2). It is during these intermittent phases that execution time can be lost, as body parts are adjusted
to execute the next technique. When training these combinations, more attention should be paid to making these periods as efficient and smooth as possible, with little auxiliary movement.

The study also found that changes observed at target contact of the techniques may be related to different initial conditions. Hence, standardising the execution of the first technique of the combination for each individual should result in a more consistent execution of the entire combination. Although in a competition fight, the initial conditions are to a certain extent determined by the opponent’s movements, a drilled standardized execution should allow the athlete to use a finite amount of time to recreate, to a certain extent, the standardized initial conditions from training, and then reproduce the combination in a consistent manner (Rothwell & Valls-Solé, 2002).

Some subjects completed the first technique of a combination in more time in 100% mode which allowed them to travel further and increase the average speed of the technique by pushing forward more (§7.3.1 and §7.3.5). However, for the purposes of competition this approach may prove detrimental as more cues are presented to the opponent (Mori et al., 2002) who may intercept the attack, rendering the remainder of the combination obsolete. A more relaxed execution of the initial technique covering sub-maximal distance in less time may be more beneficial (Jessop & Pain, 2004).

### 7.6.2. Recommendations for injury prevention

Data from this study showed that substantial variability in moments occurs in the back and non-kicking leg segments, e.g. fig. 5.45-5.46 and fig. 5.63-5.65, which could indicate that if insufficiently conditioned, these areas may be prone to chronic injury. In fact, the TKD performance director indicated when informed of these observations, that most athletes suffer from chronic injuries in the back and in the knee of the support leg which are believed to be related to the nature of the turning kick.

When examining the moment data for the central segments of an individual, it appeared that for TKD kick 3 in particular, and to some extent for TKD kick 1 and the karate kick, large variations between trials about certain axes occurred (table 7.3). This may be an indication of weakness in these areas that may make tissues prone to musculoskeletal injury (Vibert et al., 2001).
Table 7.3: Summary of the reproducibility of joint moments in the back segments during the kicks (adapted from Roosen & Pain, 2007b) (Axes are defined as per §4.4.6) (√ is reproducible; × not reproducible)

<table>
<thead>
<tr>
<th></th>
<th>Head-and-neck</th>
<th>Upper Back</th>
<th>Lower Back</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKD kick 1</td>
<td>√</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>TKD kick 2</td>
<td>×</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>TKD kick 3</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Karate kick</td>
<td>√</td>
<td>√</td>
<td>×</td>
</tr>
</tbody>
</table>

Comparing directional moments of adjacent central segments revealed that stresses in lateral directions may occur in the spine (fig. 7.6), which may indicate that extra training considerations are needed to avoid injury to the spine and postural muscles, especially given the kicks’ explosive nature (Roosen & Pain, 2007b).

Valgus-varus moments and longitudinal moments in the knee of the supporting leg also demonstrated large moments which were very variable between trials. Injuries to the knee occur if the athlete does not rotate the foot out far enough in round or turning kicks, similarly to when a footballer’s studs get stuck in the turf when trying to kick the ball. In martial arts their nature is generally chronic, and only occasionally acute, however. Conditioning of the relevant muscles should help limit the occurrence of this injury, although ultimately one should ensure an adequate twisting technique of the supporting leg is employed.
7.6.3. *Recommendation specific to the execution of the TKD combination*

Data from this study have also indicated that athletes change the execution of the technique based on their perception of the target (§7.3.2 and table 5.7). TKD athletes generally practise kicking combinations on floppy target paddles (fig. 7.7) which this study implies are kicked differently to hard targets. Training with such targets will reinforce an execution of a kick which is not maximising impact (Pieter & Pieter, 1995).

![Floppy target paddle typically used for TKD. The paddle is held by the narrow end. Kicks contact the paddle on the round surface from the side with the instep of the foot (www.superfoots.com).](image1)

It is imperative that combinations are trained on targets which can be hit or kicked with the amount of force typical of competition. This may be difficult to implement in some cases as practising combinations requires a second person to hold easy-to-manipulate targets whilst moving with the attacker. However, special protective body armour exists, better than that currently worn by TKD athletes, and typically used in boxing and Thai boxing training (fig. 7.8). Rather than holding a target, a second person who is fully mobile and protected becomes the target, so the athletes can move with them and throw punching and/or kicking combinations with full force. Such representative training should not replace practising with focus pads or paddles but must form a part of the overall training regime, so athletes can produce the combinations with the correct forces rather than practising these hard hits in isolation on a stationary heavy bag.

![Examples of protective body armour. This armour would allow the TKD athlete to train hard kicking combinations on a more representative target (www.blitzsport.com).](image2)
The aim of the TKD combination is to drive the opponent backwards with kick 1, kick 2 should then be used to attempt a score whilst the opponent is parrying and moving back from the first kick, and kick 3 should aim to score again whilst being in the air in order to avoid a counter score. When examining the durations and distances for the individual techniques it appears that athletes follow this aim, since most subjects cover more ground for kick 1 in 100% mode, and produce kick 2 and kick 3 in less time. However, the kicking leg may not be producing movements to optimally support this aim.

The data suggested that due to the low detriments in kicks 1 and 3, TKD athletes were more likely to impact harder with these kicks than with kick 2, for which a lot of speed is lost and a high stretch is reached (table 5.5-5.6). Normalised average contact velocities for kick 2 decreased in 100% mode but increased for kicks 1 and 3 (table 5.6). The average normalised stretch is largest for kick 2 and lowest for kick 3 (table 5.6).

Most TKD athletes seemed to use kick 2 as a set-up move for kick 3 rather than attempting to score. Only TKD2 appeared to use a different strategy in which impact for kick 2 was maximised, but detriments were higher for kick 1. Hence, either kick 1 or kick 2 were used mainly for the purpose of maximising the impact of the subsequent kick and these two trends seemed to become more pronounced in 100% mode.

7.6.4. Recommendations specific to the execution of the karate combination

For the karate combination, the aim of the first punch is to catch the opponent by surprise, get within their space and possibly score or at least move their guard up. The athlete needs to cover the space in a short amount of time and the punch needs to be quick. As the opponent starts to move back, hopefully exposing the body, the second punch aims to drive deep into the body, covering a lot of distance. If this does not result in a score due to the opponent moving back and getting the torso out of the way, their guard should have dropped and they should now be in range for the high-scoring kick (§1.2.2). However, an athlete will use feedback from the second punch contact to adjust the kick. If they get a good hit in this punch, it means the opponent has not stepped back very far yet and the kick may need to be executed with a smaller or no step up or more time is available to place the kick. If no or poor contact is made with the punch, the opponent has moved backward far enough to do the step up and fire the kick.

The data suggested (tables 6.8-6.9) that the athletes were indeed using punch 1 to get into the opponent quickly. Low detriment values of punch 1 indicated that if the athlete does not control the mass committed to the punch and did not punch with relatively slow
velocities, a penalty is likely (§1.2.2 and §7.7.5). The second punch was driving far and hard into the opponent attempting to move them back into the kick. Most subjects managed to drive the opponent back quite far in reaction to the quick execution of punch 1, causing punch 2 to reach a large stretch. For two subjects the detriment of punch 2 seemed to indicate that the target was in close proximity and hence the step-up for the kick may be smaller or more time was available to place the kick as the opponent was still moving back. Data for KAR2 exemplified both situations. In normal mode the subject gets good contacts of punch 2 whereas in 100% mode there was marked drop in contact velocity and detriments and stretches are larger indicating the target was hit later in the punch's motion due to the movement of the opponent. The kick was executed with high velocity but the high detriments suggested that the athlete was conscious of the contact requirements with the target. As with punch 1, the athlete needs to control the effective mass committed to the head kick as contact velocities were relatively high. These touch control requirements and how the karate athlete appears to cope with them when attacking the head, are addressed with regard to motor control in §7.7.5.

7.6.5. Summary of recommendations

Based on the observations made in this study, it would seem pertinent that the following areas need to be addressed in the training of elite martial athletes.

- conditioning the limbs that will execute the strike;
- conditioning the support structures such as the core and supporting leg(s) in order to accommodate the high speeds of the strikes;
- practising the moves in combination rather than in isolation as the athletes must learn how the segments interact when in motion rather than static;
- practising the combination on targets that are representative of the competition conditions and the movement of which is representative of competition, so techniques can be trained with the adequate amount of force and body movement; and
- eliminating unnecessary movements from the sections concerned with the initiation and continuation phases of the combination.
7.7 Motor Control

The kinematic and kinetic observations made in this study provided information on several motor control topics. In this section, these findings are discussed and related to areas that are commonly studied in the field of motor control.

7.7.1. Evidence in support of generalised motor programs in motor control

The generalised motor program (GMP) is a prestructured set of central commands based on open-loop control which is believed to govern fast movements, demonstrating both force and time rescalability (§2.2.2). This study demonstrated that joint moments were repeatable within and between execution modes, and were rescalable, i.e. the order and phasing of actions resulting in the observed joint moments were repeatable. These observations support the GMP theory. The increase in moment variability observed in moment time histories after kick contact when progressing to the next phase, can be interpreted as the end of a unit of action and the start of a new one (Schneider & Schmidt, 1995; Schmidt & Lee, 1999).

Hence, if GMPs are used for the control of movements in these martial arts combinations, a minimum of three seem to be present, i.e. one for each technique. For karate this could not be determined as moment data were only available for the kick, however it would seem logical to assume a similar increase in variability was present in the transfer phases between techniques. It is possible that more than one GMP was used for each individual technique, however, the data in this study were insufficient to investigate this.

The detriment data of this study showed that subjects will alter the acceleration-deceleration pattern of the striking limb based on the perceived integrity of the target. If the target was not likely to offer much resistance, the extension of the limb was slowed down by the athlete prior to target contact to avoid hyperextension of the knee. Certain protective reflexes and conscious alterations limiting knee extension may have been overridden when kicking a target offering more resistance. This could be an indication of different parameterisation of the same GMP as the kick was produced with higher peak velocities (§2.2.2).
7.7.2. *Evidence in support of dynamical systems in motor control*

Dynamical systems theory in motor control assumes that the interaction of the body, environment and the task can yield many valid complex outputs. The data showed that even though certain sections of the body showed large variability, techniques all hit the target pads and therefore the goal was always achieved, indicating a blending of open- and closed-loop control (Schmidt & Lee, 1999). The variability may therefore be interpreted as a feature of adaptive control to changing conditions to still produce the desired goal (Riccio, 1993; Glazier et al., 2003), as suggested by dynamical systems theory for motor control.

Moments of the kicking leg were very well defined in all cases and variability was more apparent in the other segments. Hence, the dynamical interaction of the kicking limb with the rest of the body may have led to the observed variability increase in 100% mode in order to maintain the successful execution and continuation of the combination. The codification of a complex movement like a martial arts technique may therefore be more ‘rigid’ for certain body parts, i.e. those exhibiting ballistic actions and more ‘free’ for others, governing movement corrections of the technique (Zehr et al., 1997).

Another possible indication of dynamical interaction comes from the kinematic data of this study which suggested that peak velocities of a technique could occur at different stretch values, and often different to the 70-80% quoted in literature (Atha et al., 1985). Data appeared to indicate that for the techniques examined there may be a relationship between the magnitude of the peak velocity and the point during the technique at which it occurred. The acceleration and deceleration of the limb, i.e. the concentric and eccentric forces, may not be symmetric and deceleration may be delayed (Schmidt et al., 1979) and it has been shown that they can be controlled independently (Cooke & Browne, 1990). This may suggest that the force and duration of the movement may influence the relationship between the magnitude of peak velocity and its occurrence during the movement.

7.7.3. *Speed-accuracy trade-off in martial arts strikes*

For fast aimed movements a linear speed-accuracy trade-off (SATO) is believed to exist (Plamondon & Alimi, 1997; Schmidt & Lee, 1999). Experiments into this phenomenon are conducted using different movement times (MT) with constant movement amplitude (A). MTs are typically very low, but not minimal. Where MTs are minimal, i.e.
move as fast as possible for a certain amplitude, the SATO has been shown to not necessarily be linear (Zelasnik et al., 1988).

The linear SATO in basic terms predicts that for a certain $A$, reducing MT reduces spatial accuracy and increases temporal accuracy. If the MT is kept constant and $A$ increases, spatial accuracy also decreases. In this study, neither of these values was kept constant. The data showed that MT was generally decreased in 100% mode but information on $A$ is not as apparent. The closest indicator for $A$ is the distance travelled in a technique, the change in which differed between subjects and techniques. Given this information, and the fact that data from the target pad were inconclusive (§7.3.3 and §7.3.7), no comments on the nature of the SATO in these techniques can be made.

Impulse-variability theories work from the premise that rapid movements are controlled by a single impulse (Schmidt & Lee, 1999). At low force levels the impulse-variability theories reproduce the linear SATO. However, since force variability lies at the foundation of impulse-variability theories, they also indirectly suggest that spatial accuracy may increase at near maximal force levels (§2.2.2).

Data obtained in this study (§5.3.3 and §6.3.3) showed that even though most subjects executed their techniques with a higher peak velocity in 100% mode, some produce a higher number of accurate hits and others a lower number. For the recorded accurate hits, the impact force is not always increased. Presumably, the forces developed in the muscles that govern the striking limb are high and comparable between execution modes and therefore should have comparable force variability as peak moments of the kicking leg were comparable for both modes, e.g. figures 5.4 and 6.4 (Schmidt & Lee, 1999), although it is impossible to say for certain which side of the 65% of maximum force production they lie on. It is likely that they are the maximal force that can be produced for the technique since peak velocities between execution modes were generally similar in magnitude (tables 5.6 and 6.8). It may also be incorrect to assume that a technique executed over this amplitude and involving whole-body coordination is governed by a single impulse.

Data from this study therefore are inconclusive with regard to the applicability of linear SATOs and impulse-variability theories to martial arts techniques. A more tailor-made study is required to ascertain whether or not these principles apply. Techniques will have to be executed in isolation with amplitude controlled. Even then, different results to those in the literature are expected as these striking techniques are hardly simple aimed movements. It would be interesting to compare techniques executed in isolation and in
combination and in particular how relationships between movement velocity and accuracy change between these two performance types. In order to relate force production, spatial accuracy and impact force, such experiments should also include a more sophisticated instrumented target which can give the exact location of where and with what force it is hit (§7.9.3).

Interpreting the techniques of the martial arts combinations as purely ballistic may not be correct as they are compound movements, only some parts of which are ballistic, i.e. movements of the striking limb (Zehr et al., 1997), and some parts of which are not (§2.2.2). The non-ballistic parts can therefore be altered based on feedback from the environment and from proprioception (Schmidt & Lee, 1999). As discussed in §2.2.2 even the ballistic section could, under certain conditions, be altered by some form of feedback (Brown & Loeb, 2000; Campbell & Kirkpatrick, 2001). This may be a further reason why these data cannot be used to obtain information on SATOs for these combinations.

The kinematic results of this study (§5.3.2 and §6.3.2) showed that in most cases peak velocity was reached before contact, followed by a slight deceleration. However, contact velocity never fell to zero. In some cases peak velocity occurred on or after target contact, i.e. no negative acceleration as in Schmidt et al.'s experiments (1979). It is likely therefore that some of the variability in the moment curves was caused by differences in decelerations for the individual trials, and is a further argument why the investigated martial arts techniques may not follow impulse-variability models (Zelasnik, 1993).

7.7.4. Postural control

Angle data showed that body configurations changed between execution modes. This may, to a certain degree, have been caused by postural adjustments due to changes in the kinetics of the combination as discussed in §2.2.5 and §2.2.6. Increased variability of moments of the trunk and non-kicking leg in 100% mode (table 7.3) and certain angle differences between execution modes, e.g. the angles of the front knee in punches for karate or the reduced rotation of central segments towards the kick in TKD, may be explained by anticipatory adjustments to the subsequent technique. It could be that if the athlete was consciously trying to produce a faster and/or harder technique, certain adjustments which the athlete did not consciously control, but occurred as part of the same motor program (Bouisset & Zatara, 1987), were initiated to counterbalance the more forceful execution (Bouisset & Zatara, 1981; Cordo & Nasher, 1982; Bouisset & Zatara, 1987; Béraud & Gahéry, 1995).
It would be interesting to investigate in future to what extent postural adjustments occur in progressive movements, such as those in the current study where dynamic balance is required, and examine whether the variability in moments of central segments and supporting legs is caused by a feed-forward mechanism in anticipation of a future event, or caused by a feedback mechanism based on proprioception of the current technique to compensate for the voluntary movement (Latash, 1998).

7.7.5. **Controlling energy transfer to the target**

One could expect an athlete to hit a target with less velocity if little energy is to be transferred to the target. However, a slow technique is easy to detect and therefore easy to avoid and counter. Peak and contact foot velocities of TKD and karate were not dissimilar. For TKD, peak velocities ranged from 8.5 to 14.1 m/s, and in karate 9.2-11.6 m/s; contact velocities for TKD were 8.1-13.1 m/s, and in karate 7.4-11.1 m/s. However, karate athletes must kick with touch control (§1.2.2) and were quite conscious of the contact requirements in 100% mode as indicated by the large detriments (table 6.8). As karate athletes obviously do not control energy transfer to the target with velocity, these large detriments may indicate that more time was available to ensure little effective mass contributed to the kick.

The fact that the karate athlete may control the energy transfer to the target with effective mass is supported by the generic decrease in left flexion of the trunk observed for the kick in 100% mode, i.e. the athlete leaned away from the kick more. Additionally, karate athletes retracted the shank quickly, thus minimising contact time and requiring a rapid deceleration of the foot as indicated by relatively large detriments (table 6.8), and thereby creating only a small impulse on the target.

The sequencing of the moments of leg segments may also play a role in controlling the energy transfer to the target. TKD kick 1 and kick 3, which are similar to the karate kick in terms of their movement trajectories, displayed no proximal-distal sequencing of moments whereas the karate kick did (§7.2.2 and §7.4.1). This may indicate that in karate the contact velocity is controlled by the knee and not the hip and knee. These observations are not surprising. In karate, it is easier to control the knee extension if the motion of the thigh has stopped or is decelerating. In TKD, as the foot does not need to slow down and the target can be hit as hard as the athlete chooses, a proximal-distal sequence of moments may not be required from a control accuracy point. The observations from karate are comparable to those made in other sporting movements, like throws (Feltner, 1989), that
need to be stopped before full extension is reached. Hence, proximal-distal sequencing in these types of kicks may be present to assist foot deceleration and control the contact.

Karate athletes also aimed punch 1 at the head and therefore should limit its energy transfer also. The detriments for this punch were quite low or negative for some trials for several subjects (table 6.8), i.e. the fist was still accelerating or had only marginally decelerated on contact. Presumably, the athlete is punching as fast as they can in this technique, as otherwise it would be easy to block. This is indirectly supported by athletes producing higher peak velocities in 100% mode. A low detriment coupled with a higher peak velocity in 100% mode seems to indicate the athlete has greater potential to produce a penalty hit (§1.2.2). However, the executions that were observed during the data collection were typical of those observed in competition which do not necessarily result in a contact penalty. This once again indicated that energy transfer to the target is not controlled by contact velocity, but by how much mass is committed to the punch. Also, as this punch had the lowest fist velocity, a low detriment may not create as big an issue in terms of controlling the contact.

Another reason why karate athletes may maintain low detriments for punch 1 may be related to the athlete’s perception of the movement of the target. In the data collection the person holding the target always moved back, which will have influenced the lack of ‘cautiousness’ of the attacker in delivering the punch. In competition, athletes ‘size up’ the opponent to establish whether or not the opponent reacts to an attack by backing-off or countering on the spot, and if they back-off by how far they are likely to move. When attacking to score, karate athletes adjust the range of the technique based on this feedback information. In this study, the target pad holder assumed the role of an opponent who would parry backwards if they detected the attack.

In conclusion, data from this study suggested that karate athletes do not control the energy transfer into the target when attacking the head by deliberately slowing down the fist or foot, but rather through limiting the effective mass committed to the technique. Additionally, they may keep the fist and foot less rigid on contact, thereby markedly reducing their impact potential (Asami & Nolte, 1983; Pain, 2000). In kicks to the head, a proximal-distal sequencing of moments may aid to control the energy transfer, however further research is needed to test these observations and establish whether they have an effect on the foot or fist deceleration after contact.
7.8 Limitations and assumptions of the study

7.8.1. Joint centre estimation and reconstruction

Segment definitions are primarily based on JC locations and are therefore dependent on the method of approximation and reconstruction of these JC locations. Consequently, errors in JC location will adversely affect the kinematics and kinetics of the movement under investigation. It is therefore important to estimate these locations as accurately as possible using either functional or predictive methods. Functional methods have been proposed, which have proved to be more accurate under certain conditions (Camomilla et al., 2006; Ehrig et al., 2006) than the method employed in this study (Gamage & Lasenby, 2002). Two additional experiments were conducted towards the end of this study to ascertain possible consequences of using these different JC estimation methods and to establish what errors to expect in JC reconstruction.

Recently, Camomilla et al. (2006) recommended the method of Halvorsen et al. (2003), which is that of Gamage and Lasenby (2002) extended to include a bias compensation. Hence, an experiment was conducted to ascertain how much impact this bias compensation has on approximating the hip and shoulder JCs using actual human movement data. Implementing bias compensation resulted in a change of approximately 0.1 mm in each direction compared to the method without bias compensation.

A more elaborate study (Appendix 4), showed that although the functional method proposed by Ehrig et al. (2006) can produce very accurate results for estimating JCs in theory (< 1mm), when used with real human movement data this accuracy decreased considerably. Indeed, the results indicated that determining a JC with an accuracy of greater than 20 mm is unlikely. This value is more comparable with the 13 mm RMS error found by Leardini et al. (1999) in the location of the hip JC using functional methods with a stereophotogrammetric reference. Further inaccuracies of the order of a few millimetres to tens of millimetres were introduced by the reconstruction of the estimated JC due to marker motion in reference coordinate systems used to define the JC during the activities. Similar errors can be expected for predictive JCs based on two or more markers ($4.4.7$, fig. 4.14). These results suggested that improving the theoretical accuracy of a functional method may have little influence on the accuracy of in vivo JC estimates.

Hence, the JC locations used in this study are not likely to be any less accurate during the dynamic activity than those that would have been obtained using any of the recently suggested methods. It would seem pertinent to develop further any practical measures in
situ rather than enhancing the accuracy of functional methods. Research currently ongoing within the Sports Biomechanics and Motor Control Research group as a direct result of this research and the additional study in Appendix 4 is looking into further practical improvements that can be made to enhancing JC reconstruction for athletic activity.

7.8.2. Joint moment calculation

Due to the nature of the investigation, a force plate could not be used and hence joint moments could only be calculated using inverse dynamics when no more than one foot was on the floor. In this situation, calculations can be done from the free extremities back to the foot in contact with the floor. This could not be done if both feet were on the floor as there would be more than one non-free end. Although it would have been preferable to have a force input to the inverse dynamics, the output from the model for the moments of the kicking leg were comparable to those obtained from the literature (Kerwin & Hamilton, 1987; Sørensen et al., 1997; Robertson et al., 2004).

The model is also likely to slightly underestimate joint moments for the duration that the foot is in contact with the target, as the force between the target and the foot was not taken into consideration. Further inaccuracies will have been introduced as no wobbling masses were included, which have been shown to affect the results (Aerts et al., 1995; Gruber et al., 1998; Pain & Challis, 2001, 2002; Yue & Mester, 2002). Suggestions made in §7.9.2 explain how these may be included in future.

By far the largest restriction was the limited time periods for which moments could be calculated. In order to get a deeper understanding of skill alterations for different execution modes, it will be essential to calculate their full moment time histories. This would only be possible by having a force plate under at least one foot during all the floor contacts, including the onset and transfer phases of the combination.

7.8.3. Lack of control of target movement and target data

Data from this study does not give any indication on the adaptations that were made to the combination based on the athlete's perception of the movement of the target. In general the person holding the target pads, who had ample experience, moved in such a way to allow the proper execution of the combination within the parameters of the other athlete's capability. On occasions, however, and particularly during the karate data collections, it was apparent that alterations to the execution of the technique were
instigated as a result of the movement of the target holder. It may be possible to design equipment to eliminate this undesirable factor (§7.9).

The set-up of this study did not allow for in-depth investigation into impulse-variability theories and SATOs and hence certain aspects of motor control in these combinations. The main reason for this was the limited target information. Research currently ongoing within the Sports Biomechanics and Motor Control Research Group of Loughborough University is looking into the development of an array of sensitive pressure sensors that can adequately record where and how hard a technique hits a target. Future research using and further developing such a device (§7.9) may build on the limited observations made as part of the current study.

7.9 Future research

7.9.1 Recapitulation of earlier research suggestions

Suggestions for further research already mentioned in this chapter were:

- The relationship between the approximate entropy of joint angles and of joint moments, and how these observations can help in quantifying movement variability (§7.4.3);
- Causes of movement variability in the same skill performed by different individuals (§7.5);
- The relationship between speed-accuracy trade-offs for single martial arts techniques and martial arts techniques produced as part of a combination (§7.7.3);
- The relationship between postural adjustments for a technique executed in isolation and as part of a progressive combination (§7.7.4);
- Control mechanisms of postural adjustments in progressive skills (§7.7.4);
- The relationship of proximal-distal sequencing in striking techniques with and without impact restrictions (§7.7.5);
- Practical measures to enhancing JC reconstruction for the analysis of athletic movements (§7.8.1).

Further considerations for future research are given next.
7.9.2. Data collection

With regard to data collection of complex progressive movement skills which cover a large amount of space, future research may want to investigate methods of improving the quality of the captured data. As subjects may be required to move with or around an additional object, such as an opponent or a target, marker occlusions are more likely in such studies. The adequate positioning and number of cameras become even more crucial. Improved motion capture system calibration and capturing methods may be needed for such skills, as a high degree of accuracy is required throughout the capture volume.

As discussed in §7.8.1, adequate representation of the whole body is imperative, and further studies into representing segments for athletic activities is essential. Research is being undertaken to investigate improved methods using markers (Chêze et al., 1995; Appendix 4) as well as motion capture without markers (Chaudhari et al., 2001).

Although the current study attempted to streamline the processing of motion capture data, the calculation of functional JC locations and of inertial data still had to be done outside the motion capture software and imported. Data processing would be much faster if a motion capture system could recognise a range of different trial types for different purposes, including JC and inertia estimation. The information of these special trial types could be automatically available when processing the actual movement trial of the activity under investigation. Currently, values and relationships obtained from a static trial can be used when processing movement data from dynamic trials. This could be extended to allow the inclusion of data from these other special trial types.

Initially, the motion capture system could have a particular version of these routines built in, i.e. one scientific method to obtain JC and one to obtain inertial data based on a prescribed marker set. A motion capture system typically already has routines built in for filtering, and for kinematic and kinetic calculations. Adding further routines, such as those suggested for special trial types, should not be too problematic. Ultimately, the user should be allowed to plug-in and specify their own code to do this, and the motion capture system should just require to know which program to run for what purpose, including kinematic and kinetic calculations. Hence, a Matlab compatible interface between such modules and the motion capture system would be ideal. The technology to achieve this exists, however, cooperation is required between scientists and suppliers to implement such enhancements.
7.9.3. Equipment

More specific to the current study, further tailored research will be possible if adequate equipment can be designed. Ideally, an automated target that would move based on the athlete's movements is required, i.e. a mobile base, to which a target is fixed, could be programmed to move in response to the subject's movements obtained either using a 3D motion capture system or other motion sensors. The technology to achieve this exists and has been used in gait laboratories to move x-ray cameras aimed at the knee as the subject walks through the capture volume and in biomechanics laboratories to change the movement of a six DoF platform based on those of a markered-up subject or object.

The target should also be task dependent, i.e. it could be a heavy target offering loads of resistance for hard impacts, or it could be a lighter target more suited to touch control. In an extension to this, it could also be adaptable to other sports that require the athlete to hit an object whilst moving. The target could be instrumented with arrays of pressure sensors, so that the impact location and force of a technique are known (§7.8.2, §7.8.3). Further developments could include the provision of a visual stimulus to the athlete specifying which zone of the target to attack, and could record the reaction time and accuracy of the athlete as suggested by Roosen et al. (1999). Using such a device, together with a motion capture system, would allow more insight into the mechanics and the control of complex skills of many sports involving striking movements whilst the body is in motion.

7.10 Conclusions

This study set out to identify the differences in execution of complex whole-body martial arts skills consisting of three techniques. To achieve this, novel methods of processing 3D movement data were designed which incorporated both functional and predictive JCs. A whole-body model was designed to represent the martial athletes' movements as accurately as possible. The instants of target contact were determined and used to investigate kinematic and kinetic differences between execution modes. The kinematic results identified differences in technique, end point velocities and joint angles between execution modes. The kinetic results showed which joint moment patterns were the most robust and which joint moments showed more variability.
The main conclusions of this study are:

1. The martial arts combinations were generally performed with a higher average speed in 100% mode, but strategies to achieve this varied between subjects and techniques (§7.3.1 and §7.3.5).

2. Contact velocities in 100% mode were increased by increasing peak velocities alone, and lowered by increasing detriment, i.e. inferior timing of the technique, and decreasing peak velocity (§7.3.2 and §7.3.6).

3. TKD kicks are not optimised for impact unless a suitably heavy target was kicked (§7.3.2).

4. The striking limb showed few angle differences at target contact between execution modes (§7.3.4 and §7.3.8).

5. Differences in joint angle indicated athletes may aim to reduce the transfer time between techniques and the execution time of techniques, and this appeared to be technique-specific (§7.3.4, §7.3.8 and §7.3.9).

6. Angle differences of central segments were more variable and appeared to be related to controlling the mass committed to a technique (§7.3.4 and §7.3.8).

7. Moment patterns of the kicking leg showed little variability; most moment variability was observed in central segments and in the supporting leg (§7.4.1 and §7.4.2).

8. Moments became more variable in 100% mode even though generally the moment patterns and regularity of the joint angle history were maintained.

9. Variability in support- and central segments may be a manifestation of movement adaptation in response to mechanical or proprioceptive feedback and may be an important factor in ensuring the successful outcome of the skill (§7.4.1, §7.4.2, §7.4.3 and §7.4.4).

10. When attacking the head karate athletes did not appear to control energy transfer with contact velocity. Other mechanisms such as controlling committed effective mass and sequencing of the leg extension moments are better evidenced (§7.3.8, §7.4.1 and §7.7.5).

The study also highlighted issues and made recommendations directly relevant to the athlete's development, skill enhancement and injury prevention (§7.6). Finally, questions on which to base future research related to both the motor control and biomechanics of martial arts techniques (§7.2, §7.7, §7.8, §7.9.1), and general suggestions for further research and development in equipment and methods were presented (§7.9.2, §7.9.3).
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APPENDIX 1

CONSENT FORM

This appendix contains the lay summary, information, medical questionnaire and informed consent form that were provided to all subjects that partook in this study. For all subjects signed informed consent forms were collected.
The study comprises a biomechanical analysis of human movement. This analysis requires:

- Kinematic (how you are moving), kinetic (how hard you are moving) and EMG measurements of muscle activity (how hard the muscles are working) during human movements.
- Subject specific inertia and strength parameters.

The data of actual human movements are required to give detailed information about the current techniques used by humans. The subject specific parameters are required for the customisation of computer simulation models to individual humans. The simulation models will then be used to understand and explain techniques currently used, determine the contributions of different techniques to performance and also optimise performance.

The kinematic, kinetic and EMG data may be obtained in a number of different ways:

- Video and cinematographic recordings typically using two cameras.
- Automatic displacement acquisition system. This is similar to being videoed but reflective markers or LEDs will be taped to you and only their image recorded.
- Force measurements of contact reaction forces typically using a force plate. This involves performing actions on a set of non-moving metal scales.
- EMG data using surface electrodes. This involves adhesive discs being placed on your skin above muscles to pick up when they are working.

The subject specific parameters may be obtained from:

- Anthropometric measurements. Measuring the size of your limbs and body.

Data will be acquired in the biomechanics research facilities in the University or in other research laboratories. Any data collection session will last no longer than six hours, with the subject actively involved for only a fraction of the total time:

- Actual performance of movements: 60 minutes
- Anthropometric measurements: 30 minutes

A medical history questionnaire and full written consent will be required from the parent (if the subject is under the age of 18) or the subject prior to participation in the study.
INFORMATION FOR SUBJECTS

The study in which you have been invited to participate will involve a biomechanical analysis of human movement. The study will be divided into two parts; firstly, a video recording will be taken of you performing selected human movements. You will only be asked to perform movements that you are familiar with and feel comfortable performing. The second part of the study will involve measurements to determine the lengths, widths and circumferences of your body segments (e.g. your arms, legs, trunk and head). The measurement procedures will be described and demonstrated in advance. It may be necessary to shave certain areas of your body to attach monitoring equipment using adhesive tape. The data collected will be used to help increase our understanding of the mechanics of human movements.

You will perform the data collection in a suitable environment. The risk of injury during the data collection will be minimal since we will only ask you to perform movements with which you are familiar and comfortable. It is considered that no increased risks, discomforts or distresses are likely to result from the data collection of human movements above those associated with the normal performance of those movements.

The information obtained from the study will be collected and stored in adherence with the Data Protection Act. Whilst certain personal and training information will be required, you will be allocated a reference number to ensure that your identity and personal details will remain confidential. If you agree to take part in the study, you are free to withdraw from the study at any stage, without having to give any reasons. An opportunity will be provided in this event for you to discuss privately your wish to withdraw. A contact name and phone number will be provided to you for use if you have any queries about any part of your participation in the study.
Please read through this questionnaire, BUT DO NOT ANSWER ANY OF THE QUESTIONS YET. When you have read right through, there may be questions you would prefer not to answer. Assistance will be provided if you require it to discuss any questions on this form. In this case please tick the box labelled “I wish to withdraw” immediately below. Also tick the box labelled “I wish to withdraw” if there is any other reason for you not to take part.

Tick appropriate box

I wish to withdraw [ ]
I am happy to answer the questionnaire [ ]

If you are happy to answer the questions posed below, please proceed. Your answers will be treated in the strictest confidence.

1. Are you at present recovering from any illness or operation? YES/NO*

2. Are you suffering from or have you suffered from or received medical treatment for any of the following conditions?
   a. Heart or circulation condition
      YES/NO*
   b. High blood pressure
      YES/NO*
   c. Any orthopaedic problems
      YES/NO*
d. Any muscular problems
   YES/NO*

e. Asthma or bronchial complaints
   YES/NO*

3. Are you currently taking any medication that may affect your participation in the study?
   YES/NO*

4. Are you recovering from any injury?
   YES/NO*

5. Are you epileptic?
   YES/NO*

6. Are you diabetic?
   YES/NO*

7. Are you allergic to sticking plasters?
   YES/NO*

8. Do you have any other allergies? If yes, please give details below
   YES/NO*

   .................................................................

   .................................................................

9. Are you aware of any other condition or complaint that may be affected by participation in this study? If so, please state below;
   .................................................................

   .................................................................

   * Delete as appropriate
INFORMED CONSENT FORM (SUBJECTS)

PURPOSE
To obtain kinematic, kinetic and EMG data during human movements. To obtain subject specific inertia and joint torque parameters.

PROCEDURES
The kinematic, kinetic and EMG data of human movements will be obtained using:
  - Video and cinematographic recordings typically using two cameras
  - Automatic displacement acquisition system
  - Force measurements using target pads

A number of trials will be requested with suitable breaks to minimise fatigue and boredom.

The subject specific parameters will be obtained from:
  - Anthropometric measurements (using tape measures and specialist anthropometers)

During the measurements two researchers will be present, at least one of whom will be of the same sex as you.

QUESTIONS
The researchers will be pleased to answer any questions you may have at any time.

WITHDRAWAL
You are free to withdraw from the study at any stage, without having to give any reasons. An opportunity will be provided in this event for you to discuss privately your wish to withdraw.

CONFIDENTIALITY
Your identity will remain confidential in any material resulting from this work.

I have read the outline of the procedures which are involved in this study, and I understand what will be required by me. I have had the opportunity to ask for further information and for clarification of the demands of each of the procedures and understand what is entailed. I am aware that I have the right to withdraw from the study at any time with no obligation to give reasons for my decision. As far as I am aware I do not have any injury or infirmity which would be affected by the procedures outlined.

Name ................................................

Signed ................................................ (subject) Date ..............................

In the presence of:
Name ................................................

Signed ................................................ (parent/guardian) Date ..........................
This appendix contains an outline of basic *BodyLanguage* (OMG Plc.) and a description of the joint centre definitions used in the *Fighter* model. The full code listing of the *Fighter* model with both versions of the kinetic hierarchy is included. This means that two versions of the code exist, with only the kinetic part being different. Lastly, the joint centre routine written in MatLab is listed.
A2.1. Basic BodyLanguage:

This section contains an illustration of the BodyLanguage (OMG Plc.) commands that are used in the Fighter model, and have been adapted from the BodyBuilder Manual (Oxford Metrics Ltd., 2002(1)).

BodyLanguage uses expressions and operators. The most basic expression used is a number. This can be a number input, a single integer or real constant, or a valid combination of numbers, number operations, and number functions.

Points describe positions in space, or vectors. The same point can be described in global coordinates or in local segment coordinates. A pair of braces {} is used to construct a point from three numbers. A point expression can be a point input, numbers, or a valid combination of points, point operations, and point functions:

A vector from Marker1 to Marker2 is described by:
\[
\text{Vector} = \text{Marker2} - \text{Marker1}
\]

A vector to the midpoint of Marker1 and Marker2 is described by:
\[
\text{Vector} = (\text{Marker1} + \text{Marker2})/2
\]

In the above two examples, Vector may represent a virtual marker, i.e. not a marker which is placed on the subject, but calculated by the model. It must be included in the marker file in order to be output.

Segments are groups of points which move together and represent local coordinate systems. It can move and rotate with respect to the global reference frame. A segment is denoted by a pair of square brackets []. A segment expression can be a point and two lines in square brackets, or a valid combination of segments, segment operations, and segment functions.

\[
\text{Segment} = [A, B-A, C-A, xzy]
\]

This means that the origin of the segment will be at A and the first defining line from A to B will be used as the x-axis (§2.2.4). The second defining line from A to C is crossed with the first to give the z-axis in this case. Which means that the remaining axis, y, is calculated using the right hand rule. The axes token can be altered as required.
In some cases it may be useful to introduce an *anti-flip line*. When picking the defining lines carefully this should not be required. However, if two lines are chosen that during the course of a movement go beyond an angle of 180° then the resultant second axis will change sign, i.e. it will flip. Subsequently, the third axis will also flip. The anti-flip token ensures that the sign of the second axis is automatically negated if during the rotation the second defining line passes through the anti-flip line.

Each segment definition can be recalled and extended to represent the kinetic hierarchy and contain inertial properties. Inertial values can be entered in two ways: an anthropometric table or a direct definition. The tabular definition only allows the entry of two radii of gyration per segment: longitudinal and transverse. The direct definition which was used in the *Fighter* model allows the entry of inertial properties as vectors about each axis of the segment. The segment definition is expanded as follows:

\[
\text{Segment} = [\text{Segment}, \text{Parent}, \text{ConnectionPoint}, \$\text{SgmtMass}, \$\text{SgmtMassLoc}, \$\text{SgmtInertia}]
\]

In this definition, the first parameter recalls the previously given kinematic definition of the segment. The second and third parameters are optional. They describe which segment the current segment connects to and at what point. The fourth, fifth and sixth parameters are read in from the subject parameter (MP) file (represented by the $ sign). The fourth parameter is a number giving the segment's mass in kg. The fifth parameter is a vector in local segment coordinates describing the location of the segment's centre of mass. The last parameter is also a vector containing the three moments of inertia (MoI) about the x-, y- and z axis of the segment. A kinetic hierarchy is constructed using the ConnectionPoint and Parent parameters. If a segment does not have this information it will be regarded as a root segment (§4.4.4).

Forces and moments are expressed as vectors (points) in *BodyLanguage*, the components of which are in local terms of the segment they relate to. The *Reaction function* of a segment will yield a vector with three components. The expression

\[
\text{ReactionS} = \text{REACTION}(\text{Segment})
\]

will populate the three components of point ReactionS with vectors. Therefore ReactionS can be interpreted as a 3x3 matrix. The first vector contains the forces working on the
Segment; the second vector contains the moments working on the segment; the third vector is the point of application.

Rotations of Segments refer to their orientations relative to a global frame or to another local frame. Rotations are saved as Euler angles unless specified otherwise. A rotation is defined using a pair of brackets <>. A rotation expression can be one segment in brackets plus a token, or two segments in brackets plus a token:

\[
\text{ElbowAngles} = \langle \text{Humerus, ForeArm, yxz} \rangle
\]

The interpretation of the above statement can be done in a number of ways using either Euler or fixed angles. For an in-depth description refer to the BodyBuilder Manual, pp.94-102 (Oxford Metrics Ltd., 2002(1)). In the Fighter model angle changes are calculated using Euler or cardan angles and the output of the angle expressions represent changes about the first parent axis, the second floating axis and the last child axis (§4.4.3).

Special meanings have been assigned to * and / in point operations. They are used to transform co-ordinates from a local reference frame to the global reference frame and vice versa. If LocalPoint holds the co-ordinates of a point in the Segment reference frame, and GlobalPoint holds the co-ordinates of the same point in the global reference frame, the following expressions show how to obtain one from the other:

\[
\begin{align*}
\text{GlobalPoint} & = \text{LocalPoint}*\text{Segment} \\
\text{LocalPoint} & = \text{GlobalPoint}/\text{Segment}
\end{align*}
\]

BodyLanguage also uses a range of functions. Number functions frequently used in the Fighter model:

- 1(Point), 2(Point) or 3(Point) which is equivalent to Point(1), Point(2) or Point(3) gets the components of the Point;
- DIST(Point1, Point2) is the distance between Point1 and Point2.

Point functions frequently used in the Fighter model:

- 1(Segment), 2(Segment) or 3(Segment) which is equivalent to Segment(1), Segment(2) or Segment(3) gets the directions of the relevant axis of the Segment;
CHORD(numberA, PointI, PointJ, PointK) determines a point at a distance A from PointI in a plane formed by PointI, PointJ and PointK, forming a right angle between PointI and PointJ on the opposite side of the line from PointI to PointJ from K (see figure A2.1).

Figure A2.1: CHORD function describing a point at distance A from I in plane IJK forming a right angle between I and J on the opposite side of IJ from K (adopted from OMG Plc, 2002 (1))
A2.2. Description of joint centre and segment definitions in the Fighter model:

A range of approaches have been used to establish joint centre (JC) locations in the Fighter model. These include the JC routine for the shoulders and hips coupled with the recollection routine, and also a range of predictive methods some of which also rely on the recollection routine. Some JC locations have been derived using the functions available in the BodyLanguage script using the methods suggested in the VICON models. However, some approaches to using these techniques have been revised. In order to clarify exactly how JCs have been defined in the Fighter model they are now illustrated in order. A brief comment will be given on the method used in standard VICON models before listing the different approaches used in the Fighter model. In the Fighter model, the two versions of each JC is available. One version of the skeleton is based on the functional hip and shoulder JCs obtained using the JC routine. More distal JCs are based on these initial locations. Similarly, a predictive version of the skeleton is available by using a predictive JC for the shoulder and hip JCs and deriving distal JCs based on these locations.

Shoulder:

The standard VICON model uses the markers on top of the shoulders to find the shoulder JCs. It calculates the inter-shoulder distance in each frame, and adds a fraction of this distance to the z coordinate of the shoulder marker expressed in trunk coordinates.

This is inadequate for the following reasons. The shoulder markers can move irrespective of each other by raising one shoulder and not the other for example. A better way to determine the inter-shoulder distance is to do so in the static trial and save the value to the parameter file. It can then be recalled during the dynamic trial making the inter-shoulder distance more reliable. Additionally, the marker on top of the shoulder can move irrespective of the trunk. The constant value that is added or subtracted from the marker location may therefore be inadequate during certain movements.

The first version of shoulder JCs in the Fighter model are established using the functional JC and recollection routines. The second version uses midpoint of two markers placed on the front and back of the frontal shoulder axis.

Elbow:

The standard VICON model uses a CHORD function to locate the elbow JC. This function requires that the proximal JC has already been defined and additionally requires
an extra (virtual) marker, in this case on the arm. Using this function the JC will be a point
which is a distance equal to the elbow offset (marker diameter plus elbow width) from the
elbow marker in a plane described by the elbow marker, the shoulder JC and a virtual point
lateral to the elbow marker forming a right angle between the elbow marker and the
shoulder JC, and being on the opposite side of the virtual point outside the elbow. The
elbow JC was reconstructed by recalling the midpoint of two elbow markers placed on the
condyles during the static trial. If this option was not available as in TKD day 1, the
CHORD function using both versions of the shoulder JC was used.

Wrist:

The *Fighter* model does not require a separate hand segment, however, a wrist JC
was created to define the longitudinal axis of the forearm, and was approximated by the
midpoint of two lateral markers placed on the wrist. The standard VICON model uses the
CHORD function with the elbow JC as a base to find the wrist JC.

Hip:

The standard VICON model uses a predictive approach based on Davis *et al* (1991)
to find approximate the hip JCs. The pelvis is constructed using the four ASI markers
which display considerable movement during some of the martial arts techniques, or even
get obscured during kicks. However, presuming that the positions of these markers have
been suitably smoothed this predictive method should allow for an adequate location of the
hip joints. To avoid complications due to marker occlusions during kicks, two extra
markers were placed laterally on the pelvis. This predictive version together with the
functional hip JCs are used in the *Fighter* model.

Knee:

The knee in the standard model has been defined with the CHORD functions, and
places the knee JC in a point which is a distance equal to the knee offset (marker diameter
plus knee width) from the knee marker in a plane described by the knee marker, a virtual
point behind the ASI marker and a virtual point lateral to the knee marker forming a right
angle between the knee marker and the virtual point behind the ASI marker and being on
the opposite side of the virtual point outside of the knee. It seems illogical to use a new
virtual point since the predictive hip JC is available and VICON themselves state (OMG
Plc, 2002 (1)) that:
The CHORD function may be useful in locating the centre of the knee joint given the hip joint centre and a marker on the mid-thigh and lateral condyle of the knee. This method is used in VICON Clinical Manager and Plug in Gait gait analysis software.

In the Fighter model, like for the elbow, the midpoint of two condyle markers of the knee in the static trial is recalled, and if this was not available, the CHORD function is used, with either the functional or predictive hip JC as a basis.

Ankle:

The standard VICON model determines the ankles using the CHORD function. This approach has been used in the Fighter model as well using either version of the knee JC as a basis.

Based on the JC definitions above, segments were constructed as outlined below. Note that only one version of the script has been included below, but in the Fighter model each segment exists twice based on the alternative JC definitions described above. The full model script can be found in A2.3. below.

<table>
<thead>
<tr>
<th>Head</th>
<th>[CHead, RHead-LHead, FHead-BHead, yzx]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>[TRX0, LThorax-UThorax, BThorax-FThorax, yzx]</td>
</tr>
<tr>
<td>Upper_back</td>
<td>[mid_shoulder, rsho-mid_shoulder, mid_shoulder-T10, yzx]</td>
</tr>
<tr>
<td>Lower_back</td>
<td>[LumbO, LUM1-T10, LUM1-STRN, yzx]</td>
</tr>
<tr>
<td>Pelvis</td>
<td>[PelvO, RHJC-LHJC, PELF-SACR, yzx]</td>
</tr>
<tr>
<td>LFemur</td>
<td>[LHJC, LKJC-LHJC, LKJC-LKNE, yzx]</td>
</tr>
<tr>
<td>RFemur</td>
<td>[RHJC, RKJC-RHJC, RKNE-RKJC, yzx]</td>
</tr>
<tr>
<td>LTibia</td>
<td>[LKJC, LAJC-LKJC, LAJC-LANK, yzx]</td>
</tr>
<tr>
<td>RTibia</td>
<td>[RKJC, RAJC-RKJC, RANK-RAJC, yzx]</td>
</tr>
<tr>
<td>LFoot</td>
<td>[LAJC, LTOE-LAJC, LAJC-LANK, yzx]</td>
</tr>
<tr>
<td>RFoot</td>
<td>[RAJC, RTOE-RAJC, RAJC-RANK, yzx]</td>
</tr>
<tr>
<td>LHumerus</td>
<td>[LSJC, LEJC-LSJC, LEJC-LELB, yzx]</td>
</tr>
<tr>
<td>RHumerus</td>
<td>[RSJC, REJC-RSJJC, RELB-REJC, yzx]</td>
</tr>
<tr>
<td>LForearm</td>
<td>[LEJC, LWJC-LEJC, LWJC-LWRA, yzx]</td>
</tr>
<tr>
<td>RForearm</td>
<td>[REJC, RWJC-REJC, RWRA-RWJC, yzx]</td>
</tr>
</tbody>
</table>
A2.3. The *Fighter* model:

Below follows the full script of the *Fighter* model. For the study two versions of this model were used. Each version had a different kinetic hierarchy, with a different foot as root, as the script does not allow for more than one hierarchy to exist in one model (§4.4.4). The common sections of both versions of the model will be listed first, followed by both kinetic sections that both versions have in common will be listed only once.

{**VICON BodyLanguage (tm) model**}
{copyright 1995-1999 Oxford Metrics Ltd}

{this model will create 2 versions of the body}
{segments will be constructed based on predictive joint centres}
{angles and kinetic info will be prefixed by a 'G'}
{Additionally, Segments will be constructed using joint centre locations that have been logged in the parameter file. These are derived using the Gamage & Lasenby method 2002 and have been logged in a coordinate system in the parent. They will be translated and logged in terms of the moving segment}
{created by the markers remaining in the dynamic trials}

{* Author: Andy Roosen (*}
{* Date: 2005-2007 (*}

{Start of macro section*)
 {*---------------------------------*}
macro REPLACE4(pl, p2, p3, p4)
{lReplaces any point missing from set of four fixed in a segment*]
s234 = [p3,p2-p3,p3-p4]
pIV = Average(p1/s234)*s234
s341 = [p4,p3-p4,p4-p1]
p2V = Average(p2/s341)*s341
s412 = [p1,p4-p1,p1-p2]
p3V = Average(p3/s412)*s412
s123 = [p2,p1-p2,p2-p3]
p4V = Average(p4/s123)*s123
{Now only replaces if original is missing *}
p1 = p1 ? pIV
p2 = p2 ? p2V
p3 = p3 ? p3V
p4 = p4 ? p4V
endmacro

macro FORCEVECTOR(FP)
If ExistAtAll( FP )
   F_#FP = FP(1)
   M_#FP = FP(2)
   C_#FP = FP(3)
   if (ABS(F_#FP) > 10)
       P_#FP = C_#FP + \{-M_#FP(2)/F_#FP(3), M_#FP(1)/F_#FP(3), -C_#FP(3)\}
   else
       P_#FP = C_#FP
   endif
   F_#FP = F_#FP + P_#FP
OUTPUT (P_#FP, F_#FP)
EndIf
endmacro

macro DRAWBONE(Bone, BoneLabel) {* not used in this model *}
{ /* Outputs segment definition markers in Polygon format */ }
LL = Bone#Size
DD = LL/10.
WW = DD
BoneLabel#O = 0(Bone)+LL*Bone#Shift*Attitude(Bone)
BoneLabel#P = BoneLabel#O+LL*3(Bone#Scale)*3(Bone)
BoneLabel#A = BoneLabel#O+DD*1(Bone#Scale)*1(Bone)
BoneLabel#L = BoneLabel#O+WW*2(Bone#Scale)*2(Bone)
OUTPUT(BoneLabel#O, BoneLabel#P, BoneLabel#A, BoneLabel#L)
endmacro

macro SEGVIS(Segment)
ORIGIN#Segment=0(Segment)
AXISX#Segment=0(Segment)+(1(Segment)*100)
AXISY#Segment=0(Segment)+(2(Segment)*100)
AXISZ#Segment=0(Segment)+(3(Segment)*100)
output(ORIGIN#Segment, AXISX#Segment, AXISY#Segment, AXISZ#Segment)
endmacro

{ /* End of macro section */ }
{ /* Initialisations */ }
{ /* Define optional marker points */ }
OptionalPoints(LPSI, RPSI, SACR, LTIB, RTIB)
OptionalPoints(LUPA, LFRA, LWRA, LWRB, LWRI, LWRE, LFIN)
OptionalPoints(LTHI, LSHN, LHEE, LMT5, LDOR)
OptionalPoints(RUPA, RFRA, RWRA, RWRB, RWRI, RWRE, RFIN)
OptionalPoints(RTHI, RSHN, RHEE, RMT5, RDOR)
OptionalPoints(LFHD, RFHD, LBHD, RBHD, CLAV, C7, STRN, T10)
OptionalPoints(LSHO, RSHO, LELB, RELB)
OptionalPoints(LTH2, RTH2, LUPB, RUPB)

A2 - 10
OptionalPoints(LFRA,RFRA)
OptionalPoints(LHIP,RHIP)
OptionalPoints(LTOE,RTOE)

{*Set Deadband, except for static trials*}
If $Static<>1$ Deadband = $Deadband$ EndIf

Gorigin = {0,0,0}
Global = [Gorigin,{1,0,0},{0,0,1},xyz]

{*KINEMATICS*}
{*=================*}

{*Pelvis, Sacrum, and Hips*}
{*=============================*}
Replace4(LASI,RASI,RPSI,LPSI)
SACR = (LPSI+RPSI)/2 + SACR

If $Static==1$ Then {*Save average leg length as parameter*}
  LLegLength = DIST(LASI,LKNE)+DIST(LKNE,LANK)
  RLegLength = DIST(RASI,RKNE)+DIST(RKNE,RANK)
  $LegLength = (LLegLength+RLegLength)/2
  PARAM($LegLength)
EndIf

PELF = (LASI+RASI)/2

{* define origins for Pelvis and Lumbar-cord frames to facilitate inertia CoM *}
PelvO = (PELF+SACR)/2

{* define a lower point to connect lower_back with pelvis_cord for purpose of kinetics *}
LOWJC = SACR+0.2*(PELF-SACR) {*around T4?*}
OUTPUT(LOWJC)

PelvisA = [PELF,RASI-LASI,PELF-SACR,yzx]

If ($LAsisTrocanterDistance + $RAsisTrocanterDistance) <> 0 Then
  LATD = $LAsisTrocanterDistance
  RATD = $RAsisTrocanterDistance
Else
  LATD = 0.1288*$LegLength-48.56
  RATD = LATD
EndIf

C = $LegLength*0.115-15.3
InterASISDist=DIST(LASI,RASI)
aa = InterASISDist/2
mm = $MarkerDiameter/2
COSBETA = 0.951
SINBETA = 0.309
COSTHETA = 0.880
SINTHETA = 0.476
COSTHETASINBETA = COSTHETA*SINBETA
COSTHETACOSBETA = COSTHETA*COSBETA

{Predictive hips}

GLHJC = ((C*COSTHETASINBETA - (LATD + mm) * COSBETA),
-(-C*SINTHETA + aa),
-(-C*COSTHETACOSBETA - (LATD + mm) * SINBETA))*PelvisA

GRHJC = ((C*COSTHETASINBETA - (RATD + mm) * COSBETA),
-(-C*SINTHETA - aa),
-(-C*COSTHETACOSBETA - (RATD + mm) * SINBETA))*PelvisA

OUTPUT(GLHJC, GRHJC)

{Predictive Pelvis}

GPelvis = PelvO + Attitude(PelvisA)

PelvisA = (GLHJC+GRHJC)/2 + Attitude(PelvisA)

If $Static==1 Then {Save pelvis size as parameter}

$GPelvisSize = DIST(GLHJC,GRHJC)

EndIf

PARAM($GPelvisSize)

GPelvisSize = $GPelvisSize

PelvisScale = {1.2,1,1}

PelvisShift = {0,0,0}

{HipJoints (not drawn)}

GLHipJoint = GLHJC+Attitude(PelvisA)

GRHipJoint = GRHJC+Attitude(PelvisA)

{Sacrum (dummy; to establish relative pose of spine)}

GSACO = PELF + $GPelvisSize*[-1,0,0]*Attitude(GPelvis)

GSacrum = GSACO+Attitude(GPelvis)

GSacrumSize = $GPelvisSize/2

SacrumScale = {1,1,1}

SacrumShift = {0,0,0}

{NOTE: we can only do math pelvis, hips and sacrum once we have anchored our math HJC !}

{Femura}

*LKneeOS = ($MarkerDiameter+$LKneeWidth)/2

LAnkleOS = ($MarkerDiameter+$LAnkleWidth)/2

RKneeOS = ($MarkerDiameter+$RKneeWidth)/2
RAnkleOS = ($MarkerDiameter+$RAnkleWidth)/2
GLKneeOS = ($MarkerDiameter+$LKneeWidth)/2
GLAnkleOS = ($MarkerDiameter+$LAnkleWidth)/2
GRKneeOS = ($MarkerDiameter+$RKneeWidth)/2
GRAnkleOS = ($MarkerDiameter+$RAnkieWidth)/2

LKneeFlexRef = LASI + {-200,0,0}*Attitude(PelvisA)
RKneeFlexRef = RASI + LKneeFlexRef - LASI

LFemurA = \[LKNE,LKneeFlexRef-LKneeOS*2(PelvisA)-LKNE, LANK-LKNE, zyx, LTOE-LKNE\]
RFemurA = \[RKNE,RKneeFlexRef+RKneeOS*2(PelvisA)-RKNE, RANK-RKNE, zyx, RTOE-RKNE\]

 {* Get the magic for hips and knees ! *}
{* add mathematical hip joints *}
If $Static==1 Then
{ {* create the frame the coordinates in parameter file are based on *}
MLPelvis = \[LASI,RASI-LASI,LPSI-LASI,xyz\]
MRPelvis = \[RASI,LASI-RASI,RPsi-RASI,xyz\]
{* read the data in *}
PLHJC=$PLI-UC
PRIUC=$PRIUC
{* translate to global coordinates *}
GILHJC=PLHJC*MLPelvis
GIRHJC=PRIUC*MRPelvis
{*Save pelvis size as parameter*}
$PelvisSize = DIST(GILHJC, GIRHI-UC)
PARAM($PelvisSize)
PelvisSize = $PelvisSize
{* translate to the child coordinate system *
{* $MLHJC=GILHJC/LFemurA
$MRHJC=GIRHJC/RFemurA try sticking it in pelvis instead *
$MLHJC=GILI-UC/PelvisA
$MRHJC=GIRHJC/PelvisA
PARAM($MLHJC, $MRHJC)
Endif

{* add mathematical knee joints *}
If $Static==1 Then
{ {* create the frame the coordinates in parameter file are based on *}
MLThigh = \[LTHI, LTH2-LTHI, LKNE-LTHI, xyzl\]
MRThigh = \[RTHI, RTH2-RTHI, RKNE-RTHI, xyz\]

{* also log midpoint knee markers if appropriate *}
If $MIDPTS == 1
GLKJC = (LKNE+LTH2)/2
$GLKJC = GLKJC/LFemurA
GRKJC = (RKNE+RTH2)/2
$GRKJC = GRKJC/RFemurA

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PARAM($GLKJC, $GRKJC)
Endif

[* ***************************************************]
If $MIDPTS == 1
    GLKJC = $GLKJC*LFemurA
    GRKJC = $GRKJC*RFemurA
Else
    GLKJC = CHORD(LKneeOS,LKNE,GLHJC,LKNE+500*2(LFemurA))
    GRKJC = CHORD(RKneeOS,RKNE,GRHJC,RKNE-500*2(RFemurA))
Endif

GLAJC = CHORD(LAnkleOS,LANK,GLKJC,GLKJC+500*2(LFemurA))
GRAJC = CHORD(RAnkleOS,RANK,GRKJC,GRKJC-500*2(RFemurA))

LKneeFlex = [GLKJC,LKneeFlexRef-GLKJC,GLAJC,GLKJC,zxy,LTOE-GLKJC]
    RKneeFlex = [GRKJC,RKneeFlexRef-GRKJC,GRAJC,GRKJC,zxy,RTOE-GRKJC]

OUTPUT(GLKJC,GRKJC,GLAJC,GRAJC)

[* LKNE and RKNE are markers on the knee epicondyles which if connected with the
LKJC or RKJC approximate the y-axes *]
[* Femur as per predictive joint centres *]
    GLFemur = [GLHJC,GLKJC,GLHJC,GLKJC-LKNE,zxy] { y axis towards body
centre! *}
    GRFemur = [GRHJC,GRKJC,GRHJC,RKNE-GRKJC,zxy]

[* Femur as per mathematical joint centres *]
[* first translate our local coordinates back to global ones! *]
[* LHJC=$MLHJC*LFemurA
    RHJC=$MRHJC*RFemurA try pelvis instead *]
    LHJC=$MLHJC*PelvisA
    RHJC=$MRHJC*PelvisA

[* LKJC=$MLKJC*LFemurA
    RKJC=$MRKJC*RFemurA *] { * decide math knees are no good! *}

If $MIDPTS == 1
    LKJC= GLKJC
    RKJC =GRKJC
Else
    LKJC = CHORD(LKneeOS,LKNE,LHJC,LKNE+500*2(LFemurA))
    RKJC = CHORD(RKneeOS,RKNE,RHJC,RKNE-500*2(RFemurA))
Endif

OUTPUT(LHJC,RHJC,LKJC,RKJC)
LumbO=PelvO

Pelvis=[PelvO,RHJC-LHJC,PELF-SACR,xyz]
SACO = PELF + $PelvisSize*{1,0,0}*Attitude(Pelvis)
Sacrum = SACO+Attitude(Pelvis)
SacrumSize = PelvisSize/2

LFemur = [LHJC,LKJC-LHJC,LKJC-LKNE,xyz] {* y axis towards body centre! *}
RFemur = [RHJC,RKJC-RHJC,RKNE-RKJC,xyz]

{*HipJoints (not drawn)*}
LHipJoint = LHJC+Attitude(Pelvis)
RHipJoint = RHJC+Attitude(Pelvis)

GLFemurSize = DIST(0(GLFemur),0(GLHipJoint))
LFemurSize = DIST(0(LFemur),0(LHipJoint))
LFemurScale = {1,1,1}
LFemurShift = {0,0,0}

GRFemurSize = DIST(0(GRFemur),0(GRHipJoint))
RFemurSize = DIST(0(RFemur),0(RHipJoint))
RFemurScale = {1,1,1}
RFemurShift = {0,0,0}

{*Tibiae*}
{*======*}

{* LANK and RANK are markers on the lateral maleoli which
  if connected with the LAJC or RAJC approximate the y-axes *}
  GLTibia = [GLKJC,GLAJC-GLKJC,GLAJC-LANK,xyz] {* y axis towards body
centre *}
  GRTibia = [GRKJC,GRAJC-GRKJC,GRAJC-LANK,xyz]

{* knee for visual inspection flexion axis *}
lglk={ 0,50,0}*GLTibia
rglk={0,-50,0}*GLTibia
lgrk={ 0,50,0}*GRTibia
rgrk={0,-50,0}*GRTibia
OUTPUT(lglk,rglk,lgrk,rgrk)

LAJC = CHORD(LAnkleOS,LANK,LKJC,LKJC+500*2(LFemurA))
RAJC = CHORD(RAnkleOS,RANK,RKJC,RKJC-500*2(RFemurA))

OUTPUT(LAJC,RAJC)

{* LANK and RANK are markers on the lateral maleoli which if connected with the LAJC
or RAJC approximate the y-axes *}
LTibia = [LKJC,LAJC-LKJC,LAJC-LANK,xyz] {* y axis towards body centre *}
RTibia = [RKJC,RAJC-RKJC,RKNE-RAJC,xyz]
LTibiaSize = DIST(0,LTibia,0,LFemur)
GLTibiaSize = DIST(0,GLTibia,0,GLFemur)
LTibiaScale = {0.9,0.93,0.93}
LTibiaShift = {0,0,-0.01}

RTibiaSize = DIST(0,RTibia,0,RFemur)
GRTibiaSize = DIST(0,GRTibia,0,GRFemur)
RTibiaScale = {0.93,0.93,0.93}
RTibiaShift = {0,0,-0.01}

[* Foot *]
[* ==== *]
LFoot = [LAJC,LTOE-LAJC,LANK-LAJC,xzy] { * y axis towards body centre *}
RFoot = [RAJC,RTOE-RAJC,RAJC-RANK,xzy]

GLFoot = [GLAJC,LTOE-GLAJC,LANK-GLAJC,xzy] { * y axis towards body centre *}
GRFoot = [GRAJC,RTOE-GRAJC,GRAJC-RANK,xzy]

If $Static == 1 Then
   If $StaticFootFlat == 1 Then
      LRF = {1(LAJC),2(LAJC),3(LTOE)}
      RRF = {1(RAJC),2(RAJC),3(RTOE)}
      LFootRef = [LTOE,LTOE-LRF,LAJC-LKJC,xzy]
      RFootRef = [RTOE,RTOE-RRF,RAJC-RKJC,xzy]
      GLRF = {1(GLAJC),2(GLAJC),3(LTOE)}
      GRRF = {1(GRAJC),2(GRAJC),3(RTOE)}
      GLFootRef = [LTOE,LTOE-LRF,GLAJC-GLKJC,xzy]
      GRFootRef = [RTOE,RTOE-RRF,GRAJC-GRKJC,xzy]
   Else
      LFootRef = [LTOE,LTOE-LHEE,LAJC-LKJC,xzy]
      RFootRef = [RTOE,RTOE-RHEE,RAJC-RKJC,xzy]
      GLFootRef = [LTOE,LTOE-LHEE,GLAJC-GLKJC,xzy]
      GRFootRef = [RTOE,RTOE-RHEE,GRAJC-GRKJC,xzy]
   EndIf

$LAnkleFlexOS = 1(<LFootRef,LFoot,yzx>)
$RAnkleFlexOS = 1(<RFootRef,RFoot,yzx>)
$GLAnkleFlexOS = 1(<GLFootRef,GLFoot,yzx>)
$GRAnkleFlexOS = 1(<GRFootRef,GRFoot,yzx>)

If ExistAtAll(LHEE,RHEE) Then
   $LFootLength = 1.1*DIST(LTOE,LHEE)-mm
   $RFootLength = 1.1*DIST(RTOE,RHEE)-mm
   $GLFootLength = 1.1*DIST(LTOE,LHEE)-mm
   $GRFootLength = 1.1*DIST(RTOE,RHEE)-mm
Else
   $LFootLength = 1.34*DIST(LTOE,LAJC)
   $RFootLength = 1.34*DIST(RTOE,RAJC)
$GLFootLength = 1.34 \times \text{DIST}(LTOE, GLAJC) = 1.34 \times \text{DIST}(LTOE, GLAJC)

EndIf

PARAM($LAnkleFlexOS, $RAnkleFlexOS, $LFootLength, $RFootLength)
PARAM($GLAnkleFlexOS, $GRAnkleFlexOS, $GLFootLength, $GRFootLength)

EndIf

\text{LFoot} = \text{ROT}(\text{LFoot}, 2(\text{LFoot}), (\text{$LAnkleFlexOS +5$}))
\text{RFoot} = \text{ROT}(\text{RFoot}, 2(\text{RFoot}), (\text{$RAnkleFlexOS +5$}))
\text{GLFoot} = \text{ROT}(\text{GLFoot}, 2(\text{GLFoot}), (\text{$GLAnkleFlexOS +5$}))
\text{GRFoot} = \text{ROT}(\text{GRFoot}, 2(\text{GRFoot}), (\text{$GRAnkleFlexOS +5$}))

\text{LFootSize} = 0.76 \times \text{LFootLength}
\text{GLFootSize} = 0.76 \times \text{GLFootLength}
\text{LFootScale} = \{1,1,1\}
\text{LFootShift} = \{0.13,0,0\}

\text{RFootSize} = 0.76 \times \text{RFootLength}
\text{RFootScale} = \{1,1,1\}
\text{RFootShift} = \{0.13,0,0\}

{*
***************************************************
* Thorax segment *
***************************************************/

Replace4(C7,T10,CLAV,STRN)
\text{UThorax} = (C7+CLAV)/2
\text{LThorax} = (T10+STRN)/2
\text{FThorax} = (CLAV+STRN)/2
\text{BThorax} = (C7+T10)/2

\text{TRX0} = \text{CLAV}+0.125*(\text{C7}-\text{CLAV})

{*
also define a point to connect upper_back to lower_back for the kinetics *
}
\text{MIDJC} = T10+0.125*(\text{FThorax-BThorax}) {* just in from T10 *}
\text{OUTPUT}(\text{MIDJC})

\text{Trunk} = [\text{TRX0}, \text{LThorax-UThorax}, \text{BThorax-FThorax}, \text{zyx}]

\text{If} \ \text{$Static ==1$ Then}
\ \ \ \text{ISHoDist=\text{DIST}(LSHO,RSHO)}
\ \ \ \text{PARAM(\text{ISHoDist})}
\text{Endif}

\text{ISHO} = \text{ISHoDist}
\text{GLSJC} = \text{LSHO}+(\text{ISHO}\{0,0,0.2\}+\{0,-\text{$LateralShoulderOffset,0}\})*\text{Attitude(Trunk)}
\text{GRSJC} = \text{RSHO}+(\text{ISHO}\{0,0,0.2\}+\{0,\text{$LateralShoulderOffset,0}\})*\text{Attitude(Trunk)}

\text{If ExistAtAll(LSHF,LSHB,RSHF,RSBB)
GLSJC=(LSHF+LSHB)/2
GRSJ=(RSHF+RSHB)/2
Endif

OUTPUT(GLSJC, GRSJC)

If $Static ==1 Then
    $GThoraxSize = (DIST(TRX0,GRSJ)+DIST(TRX0,GLSJ))/2
    PARAM($GThoraxSize)
EndIf

GThoraxSize = 0.9*$GThoraxSize
ThoraxScale = \{1,1,1\}
ThoraxShift = \{0,0,0\}

[*Cervical Spine (dummy; to establish alignment)*]
GCSPine = [(2*C7+CLAV)/3, CLAV-C7,-3(Trunk),xyz]

GCSpineSize = 0.5*$GThoraxSize
CSpineScale = \{1,1,1\}
CSpineShift = \{0,0,0\}

[*Head Segment*]

Replace4(LFHD, RFHD, RBHD, LBHD)
LHead = (LFHD+LBHD)/2
RHead = (RFHD+RBHD)/2
BHead = (LBHD+RBHD)/2
FHead = (LFHD+RFHD)/2

If $Static ==1 Then
    $HeadSize = DIST(FHead,BHead)
    PARAM($HeadSize)
EndIf

CHead = (FHead+BHead)/2
Head = [CHead,RHead-LHead,FHead-BHead,xyz]

If $Static == 1 Then
    HeadRef = [CHead,LHead-RHead,-3(Trunk),xyz]
    If $StaticHeadLevel == 1 Then
        $HeadFlexOS = 1(<HeadRef,Head,xyz>)
    Else
        $HeadFlexOS = 0
    EndIf
    PARAM($HeadFlexOS)
EndIf

Head = ROT(Head,2(Head),-(HeadFlexOS+HeadTilt))
HeadSize = $HeadSize
HeadScale = {1.2,1.2,1.2}
HeadShift = {0,0,-0.1}

{* need a copy for kinetic hierarchy so I haven't got 2 bodies hanging off the same head *}
Ghead=Head

{* define point need for kinetics to connect head/neck to upper_back *}
TOPJC = C7+0.125*(FHead-BHead)
OUTPUT (TOPJC)

{* ******************************************************* *}
replace4(rpsi,lpsi,lhip,rasi)
replace4(rpsi,lpsi,lhip,lasi)
output(rasi,lasi)
replace4(c7,t10,stm,clav)
output(stm)

{*Create secondary segment to reproduce mid_rasi if lost*}
mid_rlpsi=(rpsi-lpsi)/2
pelvis_cord = rpsi-lpsi
PELF2=[mid_rlpsi,pelvis_cord,lhip-rpsi,xyz]
%rasiAvTemp=AVERAGE(rasi/PELF2)
%lasiAvTemp=AVERAGE(lasi/PELF2)
IF EXIST(rasi) ELSE rasi=%rasiAvTemp*PELF2 ENDIF
IF EXIST(lasi) ELSE lasi=%lasiAvTemp*PELF2 ENDIF

{* coordinate system which has same orientation as pelvis *}
mid_rasis=(rasi+lasi)/2
{* define lower down once we have shoulders mid_shoulder=(rsjc+lsjc)/2 *}
pelvis_cord=Pelvis {* based on math joint centres *}
Gpelvis_cord=GPelvis
{* a copy with different origin to map spine! *}
pelvis_cord_spine=[LOWJC,GRHJC-GLHJC,PELF-SACR,xyz]

{*DisplayAxes(pelvis_cord)*}
rasie={800,0,0}*pelvis_cord_spine
lasie={-800,0,0}*pelvis_cord_spine
output(rasie,lasie)

lower_back=[LumbO,LUM1-t10,LUM1-STRN,xyz]
{* a copy with different origin to map spine! *}
lower_back_spine=[MIDJC,LUM1-t10,LUM1-STRN,xyz]
Glower_back=Lower_back

{*DisplayAxes(lower_back)*}
RLumbarE={-1200,0,0}*lower_back_spine
LLumbarE={1200,0,0}*lower_back_spine
output(RlumbarE, LlumbarE)

{*******************************************************************************
{Humerus Segments*}
{*******************************************************************************
If ExistAtAll(LWRA, RWRA)
    LWRI = (LWRA+LWRB)/2
    RWRI = (RWRA+RWRB)/2
EndIf

LElbowOS = ($MarkerDiameter+$LElbowWidth)/2
RElbowOS = ($MarkerDiameter+$RElbowWidth)/2

LHumerusA = [LELB, LSHO+LElbowOS*2(Trunk)-LELB, LUPB-LELB, zxy]  (*need this to hang our math. EJC off *)
RHumerusA = [RELB, RSHO-RElbowOS*2(Trunk)-RELB, RELB-RUPB, zxy]

LShoulderA = [LSHO, LSHF-LSHO, LSHB-LSHO, zxy]  (*need this to hang our math. SJC off *)
RShoulderA = [RSHO, RSHF-RSHO, RSHB-RSHO, zxy]

{* add mathematical shoulder joints *}
   If $Static==1 Then
       {* create the frame the coordinates in parameter file are based on *}
       MTrunk = [T10, STRN-T10, LUM1-T10, xyz]
       PRSJC=$PRSJC
       PLSJC=$PLSJC
       {* translate to global coordinates *}
       GILSJC=PLSJC*MTrunk
       GIRSJC=PRSJC*MTrunk
       {* translate to the child coordinate system *}
       $MLSJC=GILSJC/LShoulderA
       $MRSJC=GIRSJC/RShoulderA
       PARAM($MLSJC, $MRSJC)
   Endif

{* add mathematical elbow joints *}
   If $Static==1 Then
       {* create the frame the coordinates in parameter file are based on *}
       MLArm = [LUPA, LUPB-LUPA, LELB-LELB, xyz]
       MRArm = [RUPA, RUPB-RUPA, RELB-RUPB, xyz]
       PREJC=$PREJC
       PLEJC=$PLEJC
       {* translate to global coordinates *}
       GILEJC=PLEJC*MLArm
       GIREJC=PREJC*MRArm
       {* translate to the parent coordinate system *}
       $MLEJC=GILEJC/LHumerusA
       $MREJC=GIREJC/RHumerusA
       PARAM($MLEJC, $MREJC)
{ * also log midpoint knee markers if appropriate * }
If $MIDPTS == 1
GLEJC = (LELB+LUPB)/2
$GLEJC = GLEJC/LHumerusA
GREJC = (RELB+RUPB)/2
$GREJC = GREJC/RHumerusA
PARAM($GLEJC, $GREJC)
Endif
Endif

If $MIDPTS == 1
GLEJC = $GLEJC*LHumerusA
GREJC = $GREJC*RHumerusA
Else
GLEJC = CHORD(LElbowOS, LELB, GLSJC, LELB-500*2(LHumerusA))
GREJC = CHORD(RElbowOS, RELB, GRSJC, RELB+500*2(RHumerusA))
Endif

OUTPUT(GLEJC, GREJC)

WristOS = ($MarkerDiameter+$WristThickness)/2

{ * LELB and RELB are a marker on the elbow epicondyle which if connected with the
LEJC or REJC approximate the y-axes * }
{ * Humerus as per predictive JC * }
GLHumerus = [GLSJC, GLEJC-GLSJC, GLEJC-LELB, zxy] { * y axis towards body centre *
GRHumerus = [GRSJC, GREJC-GRSJC, RELB-GREJC, zxy]

{ * Humerus as per mathematical joint centres *}
LSJC=$MLSJC*LShoulderA
RSJC=$MRSJC*RShoulderA
MLEJC=$MLEJC*LHumerusA
MREJC=$MREJC*RHumerusA { * Decided that math elbows are no good! *}

LEJC = GLEJC
REJC = GREJC

OUTPUT(LSJC, RSJC, LEJC, REJC, MLEJC, MREJC)

{ * we have shoulders now so define this bit of spine! * }
mid_shoulder=(rsjc+lsjc)/2
Gmid_shoulder=(GRSJC+GLSJC)/2
upper_back=[mid_shoulder, rsjc-mid_shoulder, mid_shoulder-t10, yxz]
Gupper_back=[Gmid_shoulder, GRSJC-Gmid_shoulder, Gmid_shoulder-t10, yxz]
{ * a copy with different origin to map spine! * }
upper_back_spine=[TOPJC, rsho-Gmid_shoulder, Gmid_shoulder-t10, yxz]
{ *DisplayAxes(upper_back)*}
lse=[ 1500,0,0]*upper_back_spine
rse=[-1500,0,0]*upper_back_spine

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OUTPUT(rse,lse)
[* spine_cord=[SACR,mid_shoulder-SACR,mid_qlasi,zyx] *]
spine_cord=[LOWJC,TOJC-LOWJC,mid_qlasi,zyx]
spine_top={0,0,1000}*spine_cord
spine_bottom={0,0,-800}*spine_cord
output(spine_top,spine_bottom)
[* *** *]

If $Static ==1 Then

$ThoraxSize = (DIST(TRX0,RSJC)+DIST(TRX0,LSJC))/2
PARAM($ThoraxSize)
EndIf

ThoraxSize = 0.9*$ThoraxSize
CSpine = [(2*C7+CLAV)/3,CLAV-C7,-3(Trunk),xyz]
CSpineSize = 0.5*$ThoraxSize

LHumerus = [LSJC,MLEJC-LSJC,MLEJC-LELB,zyx] {* y axis towards body centre *}
RHumerus = [RSJC,MREJC-RSJC,RELB-MREJC,zyx]

{*Shoulder joint (not drawn)*}
LShJoint = LSJC+Attitude(Trunk)
RShJoint = RSJC+Attitude(Trunk)
GLShJoint = GLSJC+Attitude(Trunk)
GRShJoint = GRSJC+Attitude(Trunk)

GLHumerusSize = DIST(0(GLHumerus),0(GLShJoint))
LHumerusSize = DIST(0(LHumerus),0(LShJoint))
LHumerusScale = {1,1,1}
LHumerusShift = {0,0,0}

GRHumerusSize = DIST(0(GRHumerus),0(GRShJoint))
RHumerusSize = DIST(0(RHumerus),0(RShJoint))
RHumerusScale = {1,1,1}
RHumerusShift = {0,0,0}

{* *** *}
{* The cervical spine *}
{===============================*}

mid_back=(rbhd+lbhd)/2
mid_front=(rflid+lflid)/2
mid_head=(mid_front+mid_back)/2
SHead = [mid_head,mid_front-mid_head,rbhd-mid_back,xyz]
SHead=Rot(SHead,Shead(2),180)

SPINE(SHead,CX1,CX2,CX3,CX4,CX5,CX6,CX7,upper_back_spine)
c1=cx1(0)
c2=cx2(0)
c3=cx3(0)
c4 = cx4(0)
c5 = cx5(0)
c6 = cx6(0)
output(c1, c2, c3, c4, c5, c6)

neck_length = dist(Head(0), TOPJC)

CX1Size = neck_length/10
CX1Scale = [1.4, 1.4, 1]
CX1Shift = [0, 0, 0]
CX2Size = neck_length/10
CX2Scale = [1.4, 1.4, 1]
CX2Shift = [0, 0, 0]
CX3Size = neck_length/10
CX3Scale = [1.4, 1.4, 1]
CX3Shift = [0, 0, 0]
CX4Size = neck_length/10
CX4Scale = [1.4, 1.4, 1]
CX4Shift = [0, 0, 0]
CX5Size = neck_length/10
CX5Scale = [1.4, 1.4, 1]
CX5Shift = [0, 0, 0]
CX6Size = neck_length/10
CX6Scale = [1.4, 1.4, 1]
CX6Shift = [0, 0, 0]
CX7Size = neck_length/10
CX7Scale = [1.4, 1.4, 1]
CX7Shift = [0, 0, 0]

[* The thoracic spine *]
[*-------------------------*]

SPINE(upper_back_spine, TX1, TX2, TX3, TX4, TX5, TX6, TX7, TX8, TX9, lower_back_spine)

T1 = TX1(0)
T2 = TX2(0)
T3 = TX3(0)
T4 = TX4(0)
T5 = TX5(0)
T6 = TX6(0)
T7 = TX7(0)
T8 = TX8(0)
T9 = TX9(0)
output(T1, T2, T3, T4, T5, T6, T7, T8, T9)

thorax_length = dist(TOPJC, MIDJC)

TX1Size = 0.135*thorax_length*0.5714
TX1Scale = [1.8, 1.8, 1.0]
TX1Shift = {0,0,0}
TX2Size = 0.140*thorax_length*0.5714
TX2Scale = {1.8,1.8,1}
TX2Shift = {0,0,0}
TX3Size = 0.145*thorax_length*0.5714
TX3Scale = {1.8,1.8,1}
TX3Shift = {0,0,0}
TX4Size = 0.150*thorax_length*0.5714
TX4Scale = {1.8,1.8,1}
TX4Shift = {0,0,0}
TX5Size = 0.155*thorax_length*0.5714
TX5Scale = {1.8,1.8,1}
TX5Shift = {0,0,0}
TX6Size = 0.160*thorax_length*0.5714
TX6Scale = {1.8,1.8,1}
TX6Shift = {0,0,0}
TX7Size = 0.165*thorax_length*0.5714
TX7Scale = {1.8,1.8,1}
TX7Shift = {0,0,0}
TX8Size = 0.170*thorax_length*0.5714
TX8Scale = {1.8,1.8,1}
TX8Shift = {0,0,0}
TX9Size = 0.175*thorax_length*0.5714
TX9Scale = {1.8,1.8,1}
TX9Shift = {0,0,0}

{ * The lumbar spine * )
{ ==============================*}

SPINE(lower_back_spine,LX1,LX2,LX3,LX4,pelvis_cord_spine)

L1=LX1(0)
L2=LX2(0)
L3=LX3(0)
L4=LX4(0)
output(L1,L2,L3,L4)

lumbar_length=dist(MIDJC,LOWJC)

LX1Size = 0.135*lumbar_length*0.5714
LX1Scale = {1.8,1.8,1}
LX1Shift = {0,0,0}
LX2Size = 0.140*lumbar_length*0.5714
LX2Scale = {1.8,1.8,1}
LX2Shift = {0,0,0}
LX3Size = 0.145*lumbar_length*0.5714
LX3Scale = {1.8,1.8,1}
LX3Shift = {0,0,0}
LX4Size = 0.150*lumbar_length*0.5714
LX4Scale = {1.8,1.8,1}
LX4Shift = {0,0,0}

/* *** */

/* forearms/hands */
/* =============== */

/* don't really need a wrist joint centre, but will create a virtual marker to create */
 /* the fore-arm segment with. Markers on either side of wrist - Thumb and Pinky sides */
LWJC = (LWRA + LWRB)/2
RWJC = (RWRA + RWRB)/2

OUTPUT(LWJC, RWJC)

/* LWST and RWST are a marker on the wrist bony protrusion on the thumb side which if */
/* with the LWJC or RWJC approximate the y-axes */
GLForearm = [GLEJC, LWJC-GLEJC, LWJC-LWRA, zxy] { y axis towards body centre }
GRForearm = [GREJC, RWJC-GREJC, RWRA-RWJC, zxy]

LForearm = [MLEJC, LWJC-MLEJC, LWJC-LWRA, zxy] { y axis towards body centre }
RForearm = [MREJC, RWJC-MREJC, RWRA-RWJC, zxy]

/* the elbow for visual inspection flexion axis */
  Iglea = [0,50,0]*GLForearm
  rglea = [0,-50,0]*GLForearm
  Igrea = [0,50,0]*GRForearm
  rgrea = [0,-50,0]*GRForearm

OUTPUT(Iglea, rglea, Igrea, rgrea)

LForearmSize = DIST(0(LForearm), 0(LHumerus))
GLForearmSize = DIST(0(GLForearm), 0(GLHumerus))
LForearmScale = {0.93, 0.93, 0.93}
LForearmShift = {0,0,0}

RForearmSize = DIST(0(RForearm), 0(RHumerus))
GRForearmSize = DIST(0(GRForearm), 0(GRHumerus))
RForearmScale = {0.93, 0.93, 0.93}
RForearmShift = {0,0,0}

/*Joint Angles*/
/* ===============*/

/* *************** */
/* IMPORTANT NOTE !!! */
/* *************** */

/* as a rule flexion of the joint will be positive (y axis); */
/* internal rotation will be positive (z axis); */
Abduction will be positive (x axis) *)

(* where the angles deviate from this rule, comments will be added to illustrate the rule for that particular set of angles *)

(* First, find the general progression direction of the subject *)

PelvisDirection = AVERAGE( SACR-PELF )

If $Static == 1$ Then

Anatomy = [O(Global), 3(Global), PelvisDirection, zyx]

Else


Anatomy = [O(Global), 3(Global), Progress, zyx]

EndIf

(*Head rotates with respect to anatomical frame*)

HeadAngles = -<Anatomy, Head, yxz>

(* note: lateral rotation to the right is positive; axial rotation to the right is positive *)

(*Thorax rotates with respect to anatomical frame*)

ThoraxAngles = -<Anatomy, Trunk, yxz>

UpperThoraxAngles = -<Anatomy, upper_back, yxz>

GUpperThoraxAngles = -<Anatomy, Gupper_back, yxz>

(* note: lateral rotation to the right is positive; axial rotation to the right is positive *)

(*Pelvis rotates with respect to anatomical frame*)

PelvisAngles = -<Anatomy, Pelvis, yxz>

GPelvisAngles = -<Anatomy, GPelvis, yxz>

(* note: lateral rotation to the right is positive; axial rotation to the right is positive *)

(*Foot Progression: Feet rotate with respect to the anatomical frame*)

LFootProgressAngles = -<Anatomy, LFoot, yxz>

RFootProgressAngles = -<Anatomy, RFoot, yxz>(-1)

GLFootProgressAngles = -<Anatomy, GLFoot, yxz>

GRFootProgressAngles = -<Anatomy, GRFoot, yxz>(-1)

(* segment to segment angles *)

(* ======================== *)

(*Neck: Head rotates around Trunk *)

NeckAngles = -<Head, Trunk, yxz>

GNeckAngles = -<Ghead, Trunk, yxz>

NeckAngles2 = -<Head, upper_back, yxz>

GNeckAngles2 = -<GHead, Gupper_back, yxz>
I* note: lateral rotation to the right is positive; axial rotation to the right is positive *

I* Shoulders: Humeri rotate around the Trunk *
LShoulderAngles = -<Trunk,LHumerus,yxz>
RShoulderAngles = <Trunk,RHumerus,yxz>(-1)
GLShoulderAngles = -<Trunk,GLHumerus,yxz>
GRShoulderAngles = <Trunk,GRHumerus,yxz>(-1)
LShoulderAngles2 = -<upper_back,LHumerus,yxz>
RShoulderAngles2 = <upper_back,RHumerus,yxz>(-1)
GLShoulderAngles2 = -<Gupper_back,GLHumerus,yxz>
GRShoulderAngles2 = <Gupper_back,GRHumerus,yxz>(-1)

I* Elbows: Forearms rotate around the Humeri *
LElbowAngles = -<LHumerus,LForearm,yxz>
RElbowAngles = <RHumerus,RForearm,yxz>(-1)
GLElbowAngles = -<GLHumerus,GLForearm,yxz>
GRElbowAngles = <GRHumerus,GRForearm,yxz>(-1)

I* Whole Spine: Trunk rotates around the Pelvis *
WholeSpineAngles = -<Pelvis,Trunk,yxz>(-1)
GWholeSpineAngles = -<GPelvis,Trunk,yxz>(-1)

I* Whole Spine: Trunk rotates around the Pelvis *
WholeSpineAngles = -<Pelvis,Trunk,yxz>(-1)
GWholeSpineAngles = -<GPelvis,Trunk,yxz>(-1)

I* upper back on pelvis - compare with above *
top=<upper_back,pelvis,yxz>
Gtop=<Gupper_back,Gpelvis,yxz>

I* Upper Spine: lower rotates around upper *
UpperSpineAngles=<upper_back,lower_back,yxz>
GUpperSpineAngles=<Gupper_back,Glower_back,yxz>

I* Lower Spine: Lumbar rotates around Pelvis *
LowerSpineAngles=<lower_back,pelvis,yxz>
GLowerSpineAngles=<Glower_back,Gpelvis,yxz>

I* create normalised lumbar flexion value - or offset if static trial *
LumFlexOffset=AVERAGE(LOP)*
LSAAv=AVERAGE(LowerSpineAngles)
If $Static == 1 Then
PARAM(LSAAv)
EndIf

LSA_N = <LSA(1)-LSAAv(1),LSA(2)-LSAAv(2),LSA(3)-LSAAv(3)>

OUTPUT(LSA_N) *

(*Hips: Femurs rotate around the Pelvis *)
LHipAngles = -<Pelvis,LFemur, yxz>
RHipAngles = <Pelvis,RFemur,yxz>(-1)
GLHipAngles = -<GPelvis,GLFemur,yxz>
GRHipAngles = <GPelvis,GRFemur,yxz>(-1)

(*Knees: Tibiae rotate around the Femurs *)
LKneeAngles = -<LFemur,LTibia, yxz>(-1)
RKneeAngles = <RFemur,RTibia,yxz>
GLKneeAngles = -<GLFemur,GLTibia,yxz>(-1)
GRKneeAngles = <GRFemur,GRTibia,yxz>

(* Ankles: Feet rotate around the Tibiae *)
LAnkleAngles = -<LTibia,LFoot, yxz>
RAnkleAngles = <RTibia,RFoot,yxz>(-1)
GLAnkleAngles = -<GLTibia,GLFoot,yxz>
GRAnkleAngles = <GRTibia,GRFoot,yxz>(-1)

(* relative angles between segments *)
OUTPUT(NeckAngles,NeckAngles2,WholeSpineAngles,top,UpperSpineAngles,LowerSpineAngles)
OUTPUT(LShoulderAngles, RShoulderAngles, LShoulderAngles2, RShoulderAngles2, LElbowAngles, RElbowAngles)
OUTPUT(LHipAngles, RHipAngles, LKneeAngles, RKneeAngles, LAnkleAngles, RAnkleAngles)
OUTPUT(GNeckAngles, GNeckAngles2, GWholeSpineAngles, Gtop, GUpperSpineAngles, GLowerSpineAngles)
OUTPUT(GLShoulderAngles, GRShoulderAngles, GLShoulderAngles2, GRShoulderAngles2, GLElbowAngles, GRElbowAngles)
OUTPUT(GLHipAngles, GRHipAngles, GLKneeAngles, GRKneeAngles, GLAnkleAngles, GRAnkleAngles)

(* angles of segments with regard anatomical frame *)
OUTPUT(HeadAngles, ThoraxAngles, UpperThoraxAngles, GUpperThoraxAngles, PelvisAngles, GPelvisAngles)
OUTPUT(LFootProgressAngles, RFootProgressAngles, GLFootProgressAngles, GRFootProgressAngles)

SEGVIS(Global)
SEGVIS(Anatomy)

SEGVIS(Head)
SEGVIS(Trunk)
SEGVIS(upper_back)
SEGVIS(lower_back)
SEGVIS(LHumerus)
SEGVIS(RHumerus)
SEGVIS(LForearm)
SEGVIS(RForearm)

SEGVIS(Pelvis)
SEGVIS(LFemur)
SEGVIS(RFemur)
SEGVIS(LTibia)
SEGVIS(RTibia)
SEGVIS(LFoot)
SEGVIS(RFoot)

SEGVIS(GHead)
SEGVIS(Trunk)
SEGVIS(Gupper_back)
SEGVIS(GLowerback)

SEGVIS(GLHumerus)
SEGVIS(GRHumerus)
SEGVIS(GLForearm)
SEGVIS(GRForearm)

SEGVIS(GPelvis)
SEGVIS(GLFemur)
SEGVIS(GRFemur)
SEGVIS(GLTibia)
SEGVIS(GRTibia)
SEGVIS(GLFoot)
SEGVIS(GRFoot)

SEGVIS(LFemurA)
SEGVIS(RFemurA)
SEGVIS(PelvisA)

{* ******************************************************* *}

(* determine which foot is on the floor *)
LeftFootFloor = 0
RightFootFloor = 0
DoKinetics = 1 {* always calculate them and decide ourselves whether to use values based on foot heights *}

{* for subject determine where ankle markers are when foot is on floor *}

{* assume ankle can rise upto twice the static height and foot is still on floor ... *}

If 3(LANK) <= $LAnkleHeight*2
and 3(RANK) > $RAnkleHeight*2
{* b01 *}
LeftFootFloor = 1
DoKinetics = 1
Endif

If 3(RANK) <= $RAnkleHeight*2
    RightFootFloor = 1
    DoKinetics = 1
Endif

If 3(RANK) <= $RAnkleHeight*2
    RightFootFloor = 0.5
    LeftFootFloor = 0.5
    DoKinetics = 1
Endif

{* want to be able to verify static too *}

{* Also give me the current Ankle height as a proportion of the static average *}

LAnkleH = LANK(3)/$LAnkleHeight
RAnkleH = RANK(3)/$RAnkleHeight

OUTPUT(LLeftFootFloor, RightFootFloor, LAnkleH, RAnkleH)

END OF COMMON SECTION; BELOW FOLLOW THE TWO DIFFERENT KINETIC
SECTIONS. ONLY ONE CAN BE INCLUDED IN THE MODEL AT ANY TIME.

LEFT FOOT ROOT

{*Kinetics*}
{*==========*}

{* due to the constrictions within BodyLanguage, two hierarchies must be created. *}
{* One hierarchy has one foot as the root, the other hierarchy has the other foot. *}
{* The model needs to be run once with one hierarchy and the data needs to be saved. *}
{* Then the other hierarchy needs to be reinstated and the original commented out *}
{* and the model needs to be run once more to obtain the other kinetic data. The *}
{* RightFootFloor and LeftFootFloor flags will identify which kinetic data to use. *}

Head = [Head, upper_back, TOPJC, $HeadMass, $HeadMassLoc, $HeadInertia]

RForearm = [RForearm, RHumerus, REJC, $RForearmMass, $RForearmMassLoc, $RForearmInertia ]

RHumerus = [RHumerus, upper_back, RSJC, $RUpperArmMass, $RUpperArmMassLoc, $RUpperArmInertia]
LForearm = [LForearm, LHumerus, LEJC, LForearmMass, LForearmMassLoc, LForearmInertia] 

LHumerus = [LHumerus, upper_back, LSJC, LUpperArmMass, LUpperArmMassLoc, LUpperArmInertia] 


lower_back = [lower_back, Pelvis, LOWJC, AbdomenMass, AbdomenMassLoc, AbdomenInertia] 

{"** LEFT FOOT IS ROOT **"}

{"* functional hierarchy *}
RFoot=RFoot, RTibia, RAJC,RFootMass, RFootMassLoc, RFootInertia ] 
RTibia=RTibia, RFemur, RKJC, RTibiaMass, RTibiaMassLoc, RTibiaInertia ] 
RFemur=RFemur, Pelvis, RHJC, RFemurMass, RFemurMassLoc, RFemurInertia ] 

Pelvis = [Pelvis, LFemur, LHJC, PelvisMass, PelvisMassLoc, PelvisInertia] 

LFemur=[LFemur, LTibia, LKJC, LFemurMass, LFemurMassLoc, LFemurInertia] 
LTibia=LTibia, LFoot, LAJC, LTibiaMass, LTibiaMassLoc, LTibiaInertia ] 
LFoot=[LFoot, $LFootMass, $LFootMassLoc, $LFootInertia ] 

GHead = [GHead, Gupper_back, TOPJC, $HeadMass, $HeadMassLoc, $HeadInertia] 

GRForearm = [GRForearm, GRHumerus, GREJC, RForearmMass, RForearmMassLoc, RForearmInertia ] 

GRHumerus = [GRHumerus, Gupper_back, GRSJC, RUpperArmMass, RUpperArmMassLoc, RUpperArmInertia ] 

GLForearm = [GLForearm, GLHumerus, GLEJC, LForearmMass, LForearmMassLoc, LForearmInertia ] 

GLHumerus = [GLHumerus, Gupper_back, GLSJJC, LUpperArmMass, LUpperArmMassLoc, LUpperArmInertia ] 


{"* predictive hierarchy *}
GRFoot=[GRFoot, GRTibia, GRAJC, RFootMass, RFootMassLoc, RFootInertia ] 
GRTibia=[GRTibia, RFemur, GRKJC, RTibiaMass, RTibiaMassLoc, RTibiaInertia ] 
GRFemur=[GRFemur, GPelvis, GRHJC, RFemurMass, RFemurMassLoc, RFemurInertia ] 

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GPelvis = [GPelvis, GLFemur, GLHJC, $PelvisMass, $PelvisMassLoc, $PelvisInertia]

GLFemur=[GLFemur, GLTibia, GLKJC, $LFemurMass, $LFemurMassLoc, $LFemurInertia ]

GLTibia=[GLTibia, GLFoot, GLAIC, $LTibiaMass, $LTibiaMassLoc, $LTibiaInertia ]
GLFoot=[GLFoot, $LFootMass, $LFootMassLoc, $LFootInertia ]

If $BodyMass <> 0
and DoKinetics == 1

{* Force Vectors*}

OptionalReactions( ForcePlate1, ForcePlate2, ForcePlate3, ForcePlate4 )
ForceVector(ForcePlate1)
ForceVector(ForcePlate2)
ForceVector(ForcePlate3)
ForceVector(ForcePlate4)

{* Decompose Reactions, Normalise, Adjust Polarities, Recompose, Re-decompose!*}

{* NOTE -- ALL forces will be expressed in LOCAL terms, hence may not be parallel to
global coordinates!*}

NN = $Bodymass

{* based on functional joint centres **}

LEF = 1(REACTION(LForearm))/NN
LEF = {-1(LEF),2(LEF),-3(LEF)}
LEM = 2(REACTION(LForearm))/NN
LEM = {1(LEM),2(LEM),3(LEM)}
LForearmR = [LEF,LEM,3(REACTION(LForearm))]
LElbowForce = 1(LForearmR)
LElbowMoment = 2(LForearmR)

{* try expressing it in elbow terms as this is around the right axis *}

{* make a elbow system as per Grood and Suntay 1983 *}
LElbow=[LEJC,LWJC-LEJC,LEJC-LELB,zxy]
LElbowMomentG = LElbowMoment*LForearm
LElbowMoment2 = LElbowMomentG/LElbow

REF = -1(REACTION(RForearm))/NN
REM = 2(REACTION(RForearm))/NN
REM = {-1(REM),2(REM),-3(REM)}
RForearmR = [REF,REM,3(REACTION(RForearm))]
RElbowForce = 1(RForearmR)
\[ RElbowMoment = 2(RForearmR) \]
\[ LSF = 1(REACTION(LHumerus))/NN \]
\[ LSF = \{-1(LSF),2(LSF),-3(LSF)\} \]
\[ LSM = 2(REACTION(LHumerus))/NN \]
\[ LHumerusR = [LSF,LSM,3(REACTION(LHumerus))] \]
\[ LShoulderForce = 1(LHumerusR) \]
\[ LShoulderMoment = 2(LHumerusR) \]

{* try expressing it in elbow terms as this is around the right axis *}
{* make a elbow system as per Grood and Suntay 1983 *}
\[ RElbow=[REJC,RWJC-REJC,RELB-REJC,zxy] \]
\[ RElbowMomentG = RElbowMoment*RForearm \]
\[ RElbowMoment2 = RElbowMomentG/RElbow \]
\[ RSF = -1(REACTION(RHumerus))/NN \]
\[ RSM = 2(REACTION(RHumerus))/NN \]
\[ RSM = \{-1(RSM),2(RSM),-3(RSM)\} \]
\[ RHumerusR = [RSF,RSM,3(REACTION(RHumerus))] \]
\[ RShoulderForce = 1(RHumerusR) \]
\[ RShoulderMoment = 2(RHumerusR) \]

{* neck *}
\[ NKF = 1(REACTION(Head))/NN \]
\[ NKF = \{-1(NKF),2(NKF),-3(NKF)\} \]
\[ NKM = 2(REACTION(Head))/NN \]
\[ NKM = \{1(NKM),-2(NKM),3(NKM)\} \]
\[ HeadR = [NKF,NKM,3(REACTION(Head))] \]
\[ NeckForce = 1(HeadR) \]
\[ NeckMoment = 2(HeadR) \]

{* upper back *}
\[ UBF = 1(REACTION(upper_back))/NN \]
\[ UBF = \{-1(UBF),2(UBF),-3(UBF)\} \]
\[ UBM = 2(REACTION(upper_back))/NN \]
\[ UBM = \{1(UBM),-2(UBM),3(UBM)\} \]
\[ upper_backR = [UBF,UBM,3(REACTION(upper_back))] \]
\[ UpbackForce = 1(upper_backR) \]
\[ UpbackMoment = 2(upper_backR) \]

{* lower back *}
\[ LBF = 1(REACTION(lower_back))/NN \]
\[ LBF = \{-1(LBF),2(LBF),-3(LBF)\} \]
\[ LBM = 2(REACTION(lower_back))/NN \]
\[ LBM = \{1(LBM),-2(LBM),3(LBM)\} \]
\[ lower_backR = [LBF,LBM,3(REACTION(lower_back))] \]
\[ LobackForce = 1(lower_backR) \]
\[ LobackMoment = 2(lower_backR) \]
\[ RAF = -1(REACTION(RFoot))/NN \]
\[
\text{RAM} = 2(\text{REACTION(RFoot)})/\text{NN} \\
\text{RAM} = \{-1(\text{RAM}), 2(\text{RAM}), -3(\text{RAM})\} \\
\text{RFootR} = [\text{RAF}, \text{RAM}, 3(\text{REACTION(RFoot)})] \\
\text{RAnkleForce} = 1(\text{RFootR}) \\
\text{RAnkleMoment} = 2(\text{RFootR}) \\
\]

\[
\text{RKF} = -1(\text{REACTION(RTibia)})/\text{NN} \\
\text{RKM} = -2(\text{REACTION(RTibia)})/\text{NN} \\
\text{RTibiaR} = [\text{RKF}, \text{RKM}, 3(\text{REACTION(RTibia)})] \\
\text{RKneeForce} = 1(\text{RTibiaR}) \\
\text{RKneeMoment} = 2(\text{RTibiaR}) \\
\]

\{ * try expressing it in knee terms as this is around the right axis *\}
\{ * make a knee system as per Grood and Suntay 1983 *\}
\[
\text{RKnee} = [\text{RKJC}, \text{RAJC-RKJC}, \text{RKNE-RKJC}, zxy] \\
\text{RKneeMomentG} = \text{RKneeMoment*RTibia} \\
\text{RKneeMoment2} = \text{RKneeMomentG/RKnee} \\
\]

\[
\text{RHF} = -1(\text{REACTION(RFemur)})/\text{NN} \\
\text{RHM} = 2(\text{REACTION(RFemur)})/\text{NN} \\
\text{RFemurR} = [\text{RHF}, \text{RHM}, 3(\text{REACTION(RFemur)})] \\
\text{RHipForce} = 1(\text{RFemurR}) \\
\text{RHipMoment} = 2(\text{RFemurR}) \\
\]

\[
\text{LHF} = 1(\text{REACTION(Pelvis)})/\text{NN} \\
\text{LHF} = \{-1(\text{LHF}), 2(\text{LHF}), -3(\text{LHF})\} \\
\text{LHM} = 2(\text{REACTION(Pelvis)})/\text{NN} \\
\text{LHM} = \{1(\text{LHM}), -2(\text{LHM}), 3(\text{LHM})\} \\
\text{PelvisR} = [\text{LHF}, \text{LHM}, 3(\text{REACTION(Pelvis)})] \\
\text{LHipForce} = 1(\text{PelvisR}) \\
\text{LHipMoment} = 2(\text{PelvisR}) \\
\]

\[
\text{LKF} = 1(\text{REACTION(LFemur)})/\text{NN} \\
\text{LKF} = \{-1(\text{LKF}), 2(\text{LKF}), -3(\text{LKF})\} \\
\text{LKM} = 2(\text{REACTION(LFemur)})/\text{NN} \\
\text{LFemurR} = [\text{LKF}, \text{LKM}, 3(\text{REACTION(LFemur)})] \\
\text{LKneeForce} = 1(\text{LFemurR}) \\
\text{LKneeMoment} = 2(\text{LFemurR}) \\
\]

\{ * try expressing it in knee terms as this is around the right axis *\}
\{ * make a knee system as per Grood and Suntay 1983 *\}
\[
\text{LKnee} = [\text{LKJC}, \text{LAJC-LKJC}, \text{LKJC-LKNE}, zxy] \\
\text{LKneeMomentG} = \text{LKneeMoment*LFemur} \\
\text{LKneeMoment2} = \text{LKneeMomentG/LKnee} \\
\]

\[
\text{LAF} = 1(\text{REACTION(LTibia)})/\text{NN} \\
\text{LAF} = \{-1(\text{LAF}), 2(\text{LAF}), -3(\text{LAF})\} \\
\text{LAM} = 2(\text{REACTION(LTibia)})/\text{NN} \\
\text{LAM} = \{1(\text{LAM}), -2(\text{LAM}), 3(\text{LAM})\} \\
\]
LTibia = [LAF, LAM, 3(REACTION(LTibia))]
LAnkleForce = 1(LTibiaR)
LAnkleMoment = 2(LTibiaR)

GRF = 1(REACTION(LFoot))/NN
GRF = {-1(GRF), 2(GRF), -3(GRF)}
GRM = 2(REACTION(LFoot))/NN
LFootR = [GRF, GRM, 3(REACTION(LFoot))]
GroundRForce = 1(LFootR)
GroundRMoment = 2(LFootR)

OUTPUT(LHipMoment, RHipMoment, LKneeMoment, RKneeMoment, LAnkleMoment, RAnkleMoment, GroundRMoment)

OUTPUT(LKneeMoment2, RKneeMoment2, LElbowMoment2, RElbowMoment2)

OUTPUT(LShoulderForce, RShoulderForce, LElbowForce, RElbowForce)
OUTPUT(LShoulderMoment, RShoulderMoment, LElbowMoment, RElbowMoment)

OUTPUT(NEckForce, UpbackForce, LobackForce) /*, PelvisForce)*/
OUTPUT(NEckMoment, UpbackMoment, LobackMoment) /*, PelvisMoment)*/

OUTPUT(GLGroundRForce)

{** now for predictive equivalents **}

{ * forearm includes the hand and the mitt! * }
GLEF = 1(REACTION(GLForearm))/NN
GLEF = {-1(GLEF), 2(GLEF), -3(GLEF)}
GLEM = 2(REACTION(GLForearm))/NN
GLEM = {1(GLEM), 2(GLEM), 3(GLEM)}
GLForearmR = [GLEF, GLEM, 3(REACTION(GLForearm))]
GLElbowForce = 1(GLForearmR)
GLElbowMoment = 2(GLForearmR)

{ * try expressing it in elbow terms as this is around the right axis * }
{ * make a elbow system as per Grood and Suntay 1983 * }
GLElbow=[GLEJC, LWJC-GLEJC, GLEJC-LELB, zxy]
GLElbowMomentG = GLElbowMoment*GLForearm
GLElbowMoment2 = GLElbowMomentG/GLElbow

GREF = -1(REACTION(GRForearm))/NN
GREM = 2(REACTION(GRForearm))/NN
GREM = {-1(GREM), 2(GREM), -3(GREM)}
GRForearmR = [GREF, GREM, 3(REACTION(GRForearm))]
GRElbowForce = 1(GRForearmR)
GRElbowMoment = 2(GRForearmR)
try expressing it in elbow terms as this is around the right axis
make an elbow system as per Grood and Suntay 1983

\[ \text{GRElbow} = \{\text{GREJC}, \text{RWJC}-\text{GREJC}, \text{RELB}-\text{GREJC}, zxy\} \]
\[ \text{GRElbow Moment}_G = \text{GRElbow Moment}_G \times \text{GRforearm} \]
\[ \text{GRElbow Moment}_2 = \text{GRElbow Moment}_G / \text{GRElbow} \]

\[ \text{GLSF} = 1(\text{REACTION}(\text{GLHumerus}))/\text{NN} \]
\[ \text{GLSF} = \{-1(\text{GLSF}), 2(\text{GLSF}), -3(\text{GLSF})\} \]
\[ \text{GLSM} = 2(\text{REACTION}(\text{GLHumerus}))/\text{NN} \]
\[ \text{GLHumerus}_R = \{\text{GLSF}, \text{GLSM}, 3(\text{REACTION}(\text{GLHumerus}))\} \]
\[ \text{GLShoulderForce} = 1(\text{GLHumerus}_R) \]
\[ \text{GLShoulderMoment} = 2(\text{GLHumerus}_R) \]

\[ \text{GRSF} = -1(\text{REACTION}(\text{GRHumerus}))/\text{NN} \]
\[ \text{GRSM} = 2(\text{REACTION}(\text{GRHumerus}))/\text{NN} \]
\[ \text{GRHumerus}_R = \{\text{GRSF}, \text{GRSM}, 3(\text{REACTION}(\text{GRHumerus}))\} \]
\[ \text{GRShoulderForce} = 1(\text{GRHumerus}_R) \]
\[ \text{GRShoulderMoment} = 2(\text{GRHumerus}_R) \]

(* neck *)
\[ \text{GNKF} = 1(\text{REACTION}(\text{GHead}))/\text{NN} \]
\[ \text{GNKF} = \{-1(\text{GNKF}), 2(\text{GNKF}), -3(\text{GNKF})\} \]
\[ \text{GNKM} = 2(\text{REACTION}(\text{GHead}))/\text{NN} \]
\[ \text{GNKM} = \{1(\text{GNKM}), -2(\text{GNKM}), 3(\text{GNKM})\} \]
\[ \text{GHead}_R = \{\text{GNKF}, \text{GNKM}, 3(\text{REACTION}(\text{GHead}))\} \]
\[ \text{GNeckForce} = 1(\text{GHead}_R) \]
\[ \text{GNeckMoment} = 2(\text{GHead}_R) \]

(* upper back *)
\[ \text{GUBF} = 1(\text{REACTION}(\text{Gupper_back}))/\text{NN} \]
\[ \text{GUBF} = \{-1(\text{GUBF}), 2(\text{GUBF}), -3(\text{GUBF})\} \]
\[ \text{GUBM} = 2(\text{REACTION}(\text{Gupper_back}))/\text{NN} \]
\[ \text{GUBM} = \{1(\text{GUBM}), -2(\text{GUBM}), 3(\text{GUBM})\} \]
\[ \text{Gupper_back}_R = \{\text{GUBF}, \text{GUBM}, 3(\text{REACTION}(\text{Gupper_back}))\} \]
\[ \text{GUpbackForce} = 1(\text{Gupper_back}_R) \]
\[ \text{GUpbackMoment} = 2(\text{Gupper_back}_R) \]

(* lower back *)
\[ \text{GLBF} = 1(\text{REACTION}(\text{Glower_back}))/\text{NN} \]
\[ \text{GLBF} = \{-1(\text{GLBF}), 2(\text{GLBF}), -3(\text{GLBF})\} \]
\[ \text{GLBM} = 2(\text{REACTION}(\text{Glower_back}))/\text{NN} \]
\[ \text{GLBM} = \{1(\text{GLBM}), -2(\text{GLBM}), 3(\text{GLBM})\} \]
\[ \text{Glower_back}_R = \{\text{GLBF}, \text{GLBM}, 3(\text{REACTION}(\text{Glower_back}))\} \]
\[ \text{GLobackForce} = 1(\text{Glower_back}_R) \]
\[ \text{GLobackMoment} = 2(\text{Glower_back}_R) \]

*** LEFT FOOT IS ROOT ***
GRAF = -1(REACTION(GRFoot))/NN
GRAM = 2(REACTION(GRFoot))/NN
GRAM = \{-1(GRAM),2(GRAM),-3(GRAM)\}

GRFootR = [GRAF,GRAM,3(REACTION(GRFoot))]
GRAnkleForce = 1(GRFootR)
GRAnkleMoment = 2(GRFootR)

GRKF = -1(REACTION(GRTibia))/NN
GRKM = -2(REACTION(GRTibia))/NN

GRTibiaR = [GRKF,GRKM,3(REACTION(GRTibia))]
GRKneeForce = 1(GRTibiaR)
GRKneeMoment = 2(GRTibiaR)

* try expressing it in knee terms as this is around the right axis *
* make a knee system as per Grood and Suntay 1983 *

GRKnee=[GRKJC,GRAJC-GRKJC,RKNE-GRKJC,zxy]
GRKneeMomentG = GRKneeMoment*GRTibia
GRKneeMoment2 = GRKneeMomentG/GRKnee

GRBF = -1(REACTION(GRFemur))/NN
GRHM = 2(REACTION(GRFemur))/NN

GRFemurR = [GRBF,GRHM,3(REACTION(GRFemur))]
GRHipForce = 1(GRFemurR)
GRHipMoment = 2(GRFemurR)

GLHF = 1(REACTION(GPelvis))/NN
GLHF = \{-1(GLHF),2(GLHF),-3(GLHF)\}

GLHM = 2(REACTION(GPelvis))/NN

GPelvisR = [GLHF,GLHM,3(REACTION(GPelvis))]

GLKnee=

GLKneeMomentG = GLKneeMoment*GLFemur
GLKneeMoment2 = GLKneeMomentG/GLKnee

GLAF = 1(REACTION(GLTibia))/NN

GLAF = \{-1(GLAF),2(GLAF),-3(GLAF)\}

GLAM = 2(REACTION(GLTibia))/NN

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GLAM = \{1(GLAM),-2(GLAM),3(GLAM)\}
GLTibiaR = [GLAF,GLAM,3(REACTION(GLTibia))]
GLAnkleForce = 1(GLTibiaR)
GLAnkleMoment = 2(GLTibiaR)

GGRF = 1(REACTION(GLFoot))/NN
GGRF = \{-1(GGRF),2(GGRF),-3(GGRF)\}
GGRM = 2(REACTION(GLFoot))/NN
GLFootR = [GGRF,GGRM,3(REACTION(GLFoot))]
GGroundRForce = 1(GLFootR)
GGroundRMoment = 2(GLFootR)

OUTPUT(GLHipMoment,GRHipMoment,GLKneeMoment,GRKneeMoment,GLAnkleMoment,GRAnkleMoment,GGroundRMoment)

OUTPUT(GLKneeMoment2,GRKneeMoment2,GLElbowMoment2,GRElbowMoment2)
OUTPUT(GLShoulderForce,GRShoulderForce,GLElbowForce,GRElbowForce)
OUTPUT(GLShoulderMoment,GRShoulderMoment,GLElbowMoment,GRElbowMoment)

OUTPUT(GNeckForce,GUpbackForce,GLobackForce)
OUTPUT(GNeckMoment,GUpbackMoment,GLobackMoment)

OUTPUT(GGLGroundRForce)

EndIf

RIGHT FOOT IS ROOT

{*Kinetics*}
{*==========*}

{* due to the constrictions within BodyLanguage, two hierarchies must be created. *}
{* One hierarchy has one foot as the root, the other hierarchy has the other foot. *}
{* The model needs to be run once with one hierarchy and the data needs to be saved. *}
{* Then the other hierarchy needs to be reinstated and the original commented out *}
{* and the model needs to be run once more to obtain the other kinetic data. The *
{* RightFootFloor and LeftFootFloor flags will identify which kinetic data to use. *}

{*** RIGHT FOOT ALTERNATIVE HIERARCHY ***}

Head = [Head, upper_back, TOPJC, $HeadMass, $HeadMassLoc, $HeadInertia]
RForearm = [RForearm, RHumerus, REJC, $RForearmMass, $RForearmMassLoc, $RForearmInertia]
RHumerus = [RHumerus, upper_back, RSJC, $RUpperArmMass, $RUpperArmMassLoc, $RUpperArmInertia]
LForearm = [LForearm, LHumerus, LEJC, $LForearmMass, $LForearmMassLoc, $LForearmInertia]
LHumerus = [LHumerus, upper_back, LSJC, $LUpperArmMass, $LUpperArmMassLoc, $LUpperArmInertia]
lower_back = [lower_back, Pelvis, LOWJC, $AbdomenMass, $AbdomenMassLoc, $AbdomenInertia]

[*** RIGHT FOOT ROOT ***]
LFoot=[LFoot, LTibia, LAJC, $LFootMass, $LFootMassLoc, $LFootInertia]
LTibia=[LTibia, LFemur, LKJC, $LTibiaMass, $LTibiaMassLoc, $LTibiaInertia]
LFemur=[LFemur, Pelvis, LHJC, $LFemurMass, $LFemurMassLoc, $LFemurInertia]
Pelvis = [Pelvis, RFemur, RHJC, $PelvisMass, $PelvisMassLoc, $PelvisInertia]
RFemur=[RFemur, RTibia, RKJC, $RFemurMass, $RFemurMassLoc, $RFemurInertia]
RTibia=[RTibia, RFoot, RAJC, $RTibiaMass, $RTibiaMassLoc, $RTibiaInertia]
RFoot=[RFoot, $RFootMass, $RFootMassLoc, $RFootInertia]
GHead = [GHead, Gupper_back, TOPJC, $HeadMass, $HeadMassLoc, $HeadInertia]
GRForearm = [GRForearm, GRHumerus, GREJC, $RForearmMass, $RForearmMassLoc, $RForearmInertia]
GRHumerus = [GRHumerus, Gupper_back, GRSJC, $RUpperArmMass, $RUpperArmMassLoc, $RUpperArmInertia]
GLForearm = [GLForearm, GLHumerus, GLEJC, $LForearmMass, $LForearmMassLoc, $LForearmInertia]
GLHumerus = [GLHumerus, Gupper_back, GLSJC, $LUpperArmMass, $LUpperArmMassLoc, $LUpperArmInertia]
GLFoot=[GLFoot, GLTibia, GLAJC, $LFootMass, $LFootMassLoc, $LFootInertia]
GLTibia=[GLTibia, GLFemur, GLKJC, $LTibiaMass, $LTibiaMassLoc, $LTibiaInertia]
GLFemur=[GLFemur, GPelvis, GLHJC, $LFemurMass, $LFemurMassLoc, $LFemurInertia]
GPelvis = [GPelvis, GRFemur, GRHJC, $PelvisMass, $PelvisMassLoc, $PelvisInertia]

GRFemur=[GRFemur, GRTibia, GRKJC, $RFemurMass, $RFemurMassLoc, $RFemurInertia ]

GRTibia=[GRTibia, GRFoot, GRAJC, $RTibiaMass, $RTibiaMassLoc, $RTibiaInertia ]
GRFoot=[GRFoot, $RFootMass, $RFootMassLoc, $RFootInertia ]

If $BodyMass <> 0
and DoKinetics == 1

{*b01*}

{Force Vectors*}
{=================================*}
OptionalReactions( ForcePlate1, ForcePlate2, ForcePlate3, ForcePlate4 )
ForceVector(ForcePlate1)
ForceVector(ForcePlate2)
ForceVector(ForcePlate3)
ForceVector(ForcePlate4)

{Decompose Reactions, Normalise, Adjust Polarities, Recompose, Re-decompose!}
{=================================*}

* NOTE -- ALL forces will be expressed in LOCAL terms, hence may not be parallel to
global coordinates! *

NN = $Bodymass

{** based on functional joint centres **}

* forearm includes the hand and the mitt! *
LEF = 1(REACTION(LForearm))/NN
LEF = {1(LEF),2(LEF),3(LEF)}
LEM = 2(REACTION(LForearm))/NN
LEM = {1(LEM),2(LEM),3(LEM)}
LForearmR = [LEF,LEM,3(REACTION(LForearm))]
LElbowForce = 1(LForearmR)
LElbowMoment = 2(LForearmR)

* try expressing it in elbow terms as this is around the right axis *
* make a elbow system as per Grood and Suntay 1983 *
LElbow=([LEJC,LWJC-LEJC,LEJC-LELB,zxy]
LElbowMomentG = LElbowMoment*LForearm
LElbowMoment2 = LElbowMomentG/LElbow

REF = -1(REACTION(RForearm))/NN
REM = 2(REACTION(RForearm))/NN
REM = {1(REM),2(REM),3(REM)}
RForearmR = [REF,REM,3(REACTION(RForearm))]
RElbowForce = 1(RForearmR)
RElbowMoment = 2(RForearmR)

{"try expressing it in elbow terms as this is around the right axis *
{"make a elbow system as per Grood and Suntay 1983 *
RElbow=[REJC,RWJC-REJC,RELB-REJC,zyx]
RElbowMomentG = RElbowMoment*RForearm
RElbowMoment2 = RElbowMomentG/RElbow

LSF = 1(REACTION(LHumerus))/NN
LSF = {-1(LSF),2(LSF),-3(LSF)}
LSM = 2(REACTION(LHumerus))/NN
LHumerusR = [LSF,LSM,3(REACTION(LHumerus))]
LShoulderForce = 1(LHumerusR)
LShoulderMoment = 2(LHumerusR)

RSF = -1(REACTION(RHumerus))/NN
RSM = 2(REACTION(RHumerus))/NN
RSM = {-1(RSM),2(RSM),-3(RSM)}
RHumerusR = [RSF,RSM,3(REACTION(RHumerus))]
RShoulderForce = 1(RHumerusR)
RShoulderMoment = 2(RHumerusR)

{"neck *
NKF = 1(REACTION(Head))/NN
NKF = {-1(NKF),2(NKF),-3(NKF)}
NKM = 2(REACTION(Head))/NN
NKM = {1(NKM),-2(NKM),3(NKM)}
HeadR = [NKF,NKM,3(REACTION(Head))]
NeckForce = 1(HeadR)
NeckMoment = 2(HeadR)

{"upper back *
UBF = 1(REACTION(upper_back))/NN
UBF = {-1(UBF),2(UBF),-3(UBF)}
UBM = 2(REACTION(upper_back))/NN
UBM = {1(UBM),-2(UBM),3(UBM)}
upper_backR = [UBF,UBM,3(REACTION(upper_back))]
UpbackForce = 1(upper_backR)
UpbackMoment = 2(upper_backR)

{"lower back *
LBF = 1(REACTION(lower_back))/NN
LBF = {-1(LBF),2(LBF),-3(LBF)}
LBM = 2(REACTION(lower_back))/NN
LBM = {1(LBM),-2(LBM),3(LBM)}
lower_backR = [LBF,LBM,3(REACTION(lower_back))]
LobackForce = 1(lower_backR)
LobackMoment = 2(lower_backR)

LAF = -1(REACTION(LFoot))/NN

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LAM = 2(REACTION(LFoot))/NN
LAM = {-1(LAM),2(LAM),-3(LAM)}
LFootR = [LAF,LAM,3(REACTION(LFoot))]
LAnkleForce = 1(LFootR)
LAnkleMoment = 2(LFootR)

LKF = -1(REACTION(LTibia))/NN
LKM = -2(REACTION(LTibia))/NN
LTibiaR = [LKF,LKM,3(REACTION(LTibia))]
LKneeForce = 1(LTibiaR)
LKneeMoment = 2(LTibiaR)

LHF = -1(REACTION(LFemur))/NN
LHM = 2(REACTION(LFemur))/NN
LFemurR = [LHF,LHM,3(REACTION(LFemur))]
LHipForce = 1(LFemurR)
LHipMoment = 2(LFemurR)

RHF = 1(REACTION(Pelvis))/NN
RHF = {-1(RHF),2(RHF),-3(RHF)}
RHM = 2(REACTION(Pelvis))/NN
RHM = {1(RHM),-2(RHM),3(RHM)}
PelvisR = [RHF,RHM,3(REACTION(Pelvis))]
RHipForce = 1(PelvisR)
RHipMoment = 2(PelvisR)

RKF = 1(REACTION(RFemur))/NN
RKF = {-1(RKF),2(RKF),-3(RKF)}
RKM = 2(REACTION(RFemur))/NN
RFemurR = [RKF,RKM,3(REACTION(RFemur))]
RKneeForce = 1(RFemurR)
RKneeMoment = 2(RFemurR)

RAF = 1(REACTION(RTibia))/NN
RAF = {-1(RAF),2(RAF),-3(RAF)}
RAM = 2(REACTION(RTibia))/NN
RAM = {1(RAM),-2(RAM),3(RAM)}
RTibiaR = |RAF, RAM, 3(REACTION(RTibia))|
RAnkleForce = 1(RTibiaR)
RAnkleMoment = 2(RTibiaR)

GRF = 1(REACTION(RFoot))/NN
GRF = {-1(GRF), 2(GRF), -3(GRF)}
GRM = 2(REACTION(LFoot))/NN
RFootR = |GRF, GRM, 3(REACTION(RFoot))|
GroundRF = 1(RFootR)
GroundRM = 2(RFootR)

OUTPUT(LHipMoment, RHipMoment, LKneeMoment, RKneeMoment, LAnkleMoment, RAnkleMoment, GroundRM)

OUTPUT(LKneeMoment2, RKneeMoment2, LElbowMoment2, RElbowMoment2)

OUTPUT(LShoulderForce, RShoulderForce, LElbowForce, RElbowForce)
OUTPUT(LShoulderMoment, RShoulderMoment, LElbowMoment, RElbowMoment)

OUTPUT(NeckForce, UpbackForce, LobackForce) {*, PelvisForce}*
OUTPUT(NeckMoment, UpbackMoment, LobackMoment) {*, PelvisMoment}*

OUTPUT(GLGroundRForce)

{** now for predictive equivalents **}

(* forearm includes the hand and the mitt! *)
GLEF = 1(REACTION(GLForearm))/NN
GLEF = {-1(GLEF), 2(GLEF), -3(GLEF)}
GLEM = 2(REACTION(GLForearm))/NN
GLEM = {1(GLEM), 2(GLEM), 3(GLEM)}
GLForearmR = |GLEF, GLEM, 3(REACTION(GLForearm))|
GLElbowForce = 1(GLForearmR)
GLElbowMoment = 2(GLForearmR)

(* try expressing it in elbow terms as this is around the right axis *)
(* make a elbow system as per Grood and Suntay 1983 *)
GLElbow=[GLEJC, LWJC-GLEJC, GLEJC-LELB, zxy]
GLElbowMomentG = GLElbowMoment*GLForearm
GLElbowMoment2 = GLElbowMomentG/GLElbow

GREF = -1(REACTION(GRForearm))/NN
GREM = 2(REACTION(GRForearm))/NN
GREM = {-1(GREM), 2(GREM), -3(GREM)}
GRForearmR = |GREF, GREM, 3(REACTION(GRForearm))|
GRElbowForce = 1(GRForearmR)
GRElbowMoment = 2(GRForearmR)

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{* try expressing it in elbow terms as this is around the right axis *}
{* make a elbow system as per Grood and Suntay 1983 *}
GRElbow=[GREJC,RWJC-GREJC,RELB-GREJC, zxy]
GRElbowMomentG = GRElbowMoment*GRForearm
GRElbowMoment2 = GRElbowMomentG/GRElbow

GLSF = 1(REACTION(GLHumerus))/NN
GLSF = {-1(GLSF),2(GLSF), -3(GLSF)}
GLSM = 2(REACTION(GLHumerus))/NN
GLHumerusR = [GLSF,GLSM,3(REACTION(GLHumerus))]
GLShoulderForce = 1(GLHumerusR)
GLShoulderMoment = 2(GLHumerusR)

GRSF = -1(REACTION(GRHumerus))/NN
GRSM = 2(REACTION(GRHumerus))/NN
GRSM = {-1(GRSM),2(GRSM), -3(GRSM)}
GRHumerusR = [GRSF,GRSM,3(REACTION(GRHumerus))]GRShoulderForce = 1(GRHumerusR)
GRShoulderMoment = 2(GRHumerusR)

{* neck *}
GNKF = 1(REACTION(GHead))/NN
GNKF = {-1(GNKF),2(GNKF), -3(GNKF)}
GNKM = 2(REACTION(GHead))/NN
GNKM = {1(GNKM),-2(GNKM),3(GNKM)}
GHeadR = [GNKF,GNKM,3(REACTION(GHead))]
GNeckForce = 1(GHeadR)
GNeckMoment = 2(GHeadR)

{* upper back *}
GUBF = 1(REACTION(Gupper_back))/NN
GUBF = {-1(GUBF),2(GUBF), -3(GUBF)}
GUBM = 2(REACTION(Gupper_back))/NN
GUBM = {1(GUBM),-2(GUBM),3(GUBM)}
Gupper_backR = [GUBF,GUBM,3(REACTION(Gupper_back))]
GUpbackForce = 1(Gupper_backR)
GUpbackMoment = 2(Gupper_backR)

{* lower back *}
GLBF = 1(REACTION(Glower_back))/NN
GLBF = {-1(GLBF),2(GLBF), -3(GLBF)}
GLBM = 2(REACTION(Glower_back))/NN
GLBM = {1(GLBM),-2(GLBM),3(GLBM)}
Glower_backR = [GLBF,GLBM,3(REACTION(Glower_back))]
GLobackForce = 1(Glower_backR)
GLobackMoment = 2(Glower_backR)

GLAF = -1(REACTION(GLFoot))/NN
GLAM = 2(REACTION(GLFoot))/NN
GLAM = {-1(GLAM),2(GLAM), -3(GLAM)}
GLFootR = [GLAF, GLAM, 3(REACTION(GLFoot))]
GLAnkleForce = 1(GLFootR)
GLAnkleMoment = 2(GLFootR)

GLKF = -1(REACTION(GLTibia))/NN
GLKM = -2(REACTION(GLTibia))/NN
GLTibiaR = [GLKF, GLKM, 3(REACTION(GLTibia))]
GLKneeForce = 1(GLTibiaR)
GLKneeMoment = 2(GLTibiaR)

{ * try expressing it in knee terms as this is around the right axis * }
{ * make a knee system as per Grood and Suntay 1983 * }
GLKnee=[GLKJC, GLAJC-GLKJC, GLKJC-LKNE, zxy]
GLKneeMomentG = GLKneeMoment*GLTibia
GLKneeMoment2 = GLKneeMomentG/GLKnee

GLHF = -1(REACTION(GLFemur))/NN
GLHM = 2(REACTION(GLFemur))/NN
GLHM = {-1(GLHM), 2(GLHM), -3(GLHM)}
GLFemurR = [GLHF, GLHM, 3(REACTION(GLFemur))]
GLHipForce = 1(GLFemurR)
GLHipMoment = 2(GLFemurR)

GRHF = 1(REACTION(GPelvis))/NN
GRHF = {-1(GRHF), 2(GRHF), -3(GRHF)}
GRHM = 2(REACTION(GPelvis))/NN
GRHM = {1(GRHM), -2(GRHM), 3(GRHM)}
GPelvisR = [GRHF, GRHM, 3(REACTION(GPelvis))]
GRHipForce = 1(GPelvisR)
GRHipMoment = 2(GPelvisR)

GRKF = 1(REACTION(GRFemur))/NN
GRKF = {-1(GRKF), 2(GRKF), -3(GRKF)}
GRKM = 2(REACTION(GRFemur))/NN
GRFemurR = [GRKF, GRKM, 3(REACTION(GRFemur))]
GRKneeForce = 1(GRFemurR)
GRKneeMoment = 2(GRFemurR)

{ * try expressing it in knee terms as this is around the right axis * }
{ * make a knee system as per Grood and Suntay 1983 * }
GRKnee=[GRKJC, GRAJC-GRKJC, RKNE-GRKJC, zxy]
GRKneeMomentG = GRKneeMoment*GRFemur
GRKneeMoment2 = GRKneeMomentG/GRKnee

GRAF = 1(REACTION(GRTibia))/NN
GRAF = {-1(GRAF), 2(GRAF), -3(GRAF)}
GRAM = 2(REACTION(GRTibia))/NN
GRAM = {1(GRAM), -2(GRAM), 3(GRAM)}
GRTibiaR = [GRAF, GRAM, 3(REACTION(GRTibia))]
GRAnkleForce = 1(GRTibiaR)

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GRAnkleMoment = 2(GRTibiaR)

GGRF = 1(REACTION(GRFoot))/NN
GGRF = {-1(GGRF),2(GGRF),-3(GGRF)}
GGRM = 2(REACTION(GRFoot))/NN
GRFootR = |GGRF,GGRM,3(REACTION(GRFoot))|
GGroundRForce = 1(GRFootR)
GGroundRMoment = 2(GRFootR)

OUTPUT(GLHipMoment,GRHipMoment,GLKneeMoment,GRKneeMoment,GLAnkleMoment,GRAnkleMoment,GGroundRMoment)

OUTPUT(GLKneeMoment2,GRKneeMoment2,GLElbowMoment2,GRElbowMoment2)
OUTPUT(GLShoulderForce,GRShoulderForce,GLElbowForce,GRElbowForce)
OUTPUT(GLShoulderMoment,GRShoulderMoment,GLElbowMoment,GRElbowMoment)

OUTPUT(GNeckForce,GUpbackForce,GLobackForce)
OUTPUT(GNeckMoment,GUpbackMoment,GLobackMoment)

OUTPUT(GGLGroundRForce)

EndIf {* e01 *}

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A2.4. The Joint Centre Routine:

This next section shows the joint centre routine in MatLab code which implements the method by Gamage and Lasenby (2002).

******************************************************************************

function [Cm]=localjc3(name,M)

% this module builds on the module metodo1b of Andrea Cereatti (described below), which implements
% Gamage, Lasenby 2002, to calculate the centre of rotation. This extended module turns
% global coordinates into local coordinates of a parent frame around which
% the child is rotating before calculating the centre of rotation. The location of the centre
% of rotation will
% therefore be given as coordinates in the parent frame rather than global.
% %
% % This module requires 2 parameters:
% % The first parameter is the name of the file the joint centre location
% % vector will be stored in.
% % The second parameter is a matrix which will have the x,y,z coordinates of markers in
% % columns. The first 3 markers (9 columns) are for 3 markers in the parent
% % (giving the marker in which to locate the origin first) and subsequent
% % columns refer to the markers in the child (minimum of three markers
% % required!)
% %
% % The module will separate the input matrix into 2 matrices. The first 3
% % columns are used to transfer global coordinates in to parent coordinates
% % by construction a translation vector and a rotation matrix. These are
% % then used to convert the elements of the 2nd matrix into parent
% % coordinates. This converted matrix is then used to calculate the centre
% % of rotation as per Andreatti's code. The resultant vector is stored with
% % the filename passed into this module.
% %
% % Code added by myself will be indentified by %AR in the line
% %
% % INPUT: name - name of file to store output in
% % M - clean matrix containing markers' trajectories in the parent and child system of
% % reference.
% % dim(M)=Nc*(9+3p) where Nc is number of good samples and p is
% % the number of child markers. The 9 represents the
% % 3 markers in the parent system
% % OUTPUT: Cm - vector with the coordinates of centre of rotation (Cx,Cy,Cz).
% %
% % Author: Andy Roosen
% %
% - original description -
%******************************************************************************
% Description: Calculation of the hip joint center HJC.
% \[ Cm \] = metodolb(TrP).
% -----------------------------------------------

% INPUT: TrP clean matrix containing markers' trajectories in the proximal system of reference.
% \[ \text{dim(TrP)} = Nc \times 3p \] where \( Nc \) is number of good samples and \( p \) is the number of distal markers
% OUTPUT: \( Cm \) vector with the coordinates of hip joint center \( (Cx, Cy, Cz) \).
% -----------------------------------------------

% Comments: metodolb extracts HJC position as the centre of the optimal spherical surface that minimizes the root mean square error
% between the radius (unknown) and the distance of the centroid of marker's coordinates from sphere center (unknown).
% Using edfinition of vector differentiation is it possible to put the problem in the form: \( A \times Cm = B \) that is a linear equation system
% References: Gamage, Lasenby J. (2002).
% New least squares solutions for estimating the average centre of rotation and the axis of rotation.
% Journal of Biomechanics 35, 87-93 2002
% Author Andrea Cereatti.
% Date
% -----------------------------------------------

% separate out the parent markers

\[ \text{rm cm} = \text{size}(M); \]
\%AR begin
\text{PS} = M(1: \text{rm}, 1:9);
\%AR end

\% separate out the child markers
\text{TrP} = M(1: \text{rm}, 10: \text{cm});

\% %AR end

\% % AR begin
\[ [r c] = \text{size}(\text{TrP}); \]
\[ D = \text{zeros}(3); \]
\[ V1 = []; \]
\[ V2 = []; \]
\[ V3 = []; \]
\[ b1 = [0 0 0]; \]
\%AR end

for \( j = 1:3:c \)
\[ d1 = \text{zeros}(3); \]
\[ V2a = 0; \]
\[ V3a = [0 0 0]; \]
\%AR end

for \( i = 1:r \)
\% %AR end
\[ t = \text{PS}(i, 1:3); \]
\[ u = \text{PS}(i, 4:6); \]
\[ v = \text{PS}(i, 7:9); \]
\%AR end

\[ x = u - t; \%
\
\[ z = v-t; \] 
\[ y = \text{cross}(z,x); \] 
\[ z = \text{cross}(x,y); \]

\[ \text{ip} = x/\text{norm}(x); \] 
\[ \text{jp} = y/\text{norm}(y); \] 
\[ \text{kp} = z/\text{norm}(z); \]

% rotation matrix from global to parent is therefore the unit vectors of 
% parent expressed in global as columns:
\[ \text{ROT} = [\text{ip} \ \text{jp} \ \text{kp}]; \]

% each coordinate in TrP now needs to be transformed as follows:
% marker local = inv[C](marker global-local origin global)
% this manipulation will be done as the code below loops through the TrP
% matrix
\[
\text{L} = \text{zeros}(3);
\text{L} = \text{TrP}(i,j:j+2);
\text{L} = \text{L} - t;
\text{L} = \text{ROT}^* \text{L};
\]
for \( m = j:j+2; \)
\[
\text{TrP}(i,m) = \text{L}(m-j+1);
\]
end;

% ******************************************************* %AR end
\[
\text{d1} = (d1+\text{TrP}(i,j:j+2)) \times (\text{TrP}(i,j:j+2));
\]
\[
\text{a} = (\text{TrP}(i,j))^2 + \text{TrP}(i,j+1)^2 + \text{TrP}(i,j+2)^2;
\]
\[
\text{V2a} = \text{V2a} + a;
\]
\[
\text{V3a} = \text{V3a} + a \times \text{TrP}(i,j:j+2);
\]
end
\[
\text{D} = \text{D} + (d1/r);
\]
\[
\text{V2} = [\text{V2}, \text{V2a}/r];
\]
\[
\text{bl} = [\text{bl} + \text{V3a}/r];
\]
end
\[
\text{V1} = \text{mean} \left( \text{TrP} \right);
\]
\[
\text{p} = \text{size}(\text{V1},2);
\]
\[
\text{e1} = 0;
\]
\[
\text{E} = \text{zeros}(3);
\]
\[
\text{f1} = [0 \ 0 \ 0];
\]
\[
\text{F} = [0 \ 0 \ 0];
\]
for \( k = 1:3:p \)
\[
\text{e1} = \text{V1}(k:k+2) \times \text{V1}(k:k+2);
\]
\[
\text{E} = \text{E} + \text{e1};
\]
\[
\text{f1} = \text{V2}(k-1)/3 + 1 \times \text{V1}(k:k+2);
\]
\[
\text{F} = \text{F} + \text{f1};
\]
end

% equation (5) of Gamage and Lasenby
\[
\text{A} = 2 \times (\text{D} - \text{E});
\]
\[
\text{k} = \text{D} - \text{E};
\]
\[
\text{B} = (\text{b1} - \text{F})^*;
\]
[U,S,V] = svd(A);
Cm = V*inv(S)*U'*B;
% Save the vector
save (name,'Cm','-ASCII');
APPENDIX 3

ANTHROPOMETRIC DATA AND PARAMETER FILE

This appendix contains the anthropometric measurements taken for all subjects according to the method suggested by Yeadon (1990) followed by an example MP file in which the obtained inertia data and calculated joint centre coordinates are stored.
### A3.1 Subject anthropometric measurements

#### ANTHROPOMETRIC MEASUREMENTS FOR SEGMENTAL INERTIA PARAMETERS

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All measurements in millimetres

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All measurements in millimetres

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**AGE:** 19  
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**DATE:** 08/11/2005

**MEASURER:** MJH/AR  
**WEIGHT:** 63.2

All measurements in millimetres

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All measurements in millimetres

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**RIGHT LEG**

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# Anthropometric Measurements for Segmental Inertia Parameters

**Name:** TKD5  **Age:** 20  **Height:** 184.5  **Date:** 10/11/2005  
**Measurer:** MJH/AR  **Weight:** 67.1  
All measurements in millimetres

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All measurements in millimetres

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ANTHROPOMETRIC MEASUREMENTS FOR SEGMENTAL INERTIA PARAMETERS

NAME        KAR2  AGE  23  HEIGHT  172.0  DATE  04/03/2007
MEASURER    MJH/MTG  WEIGHT  77.1

All measurements in millimetres

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# Anthropometric Measurements for Segmental Inertia Parameters

**Name:** KAR3  |  **Age:** 26  |  **Height:** 176.3  |  **Date:** 04/03/2007

**Measurer:** MJH/MTG  |  **Weight:** 67.2

All measurements in millimetres

## Torso

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<th>Nipple</th>
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All measurements in millimetres

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A3 - 10
## ANTHROPOMETRIC MEASUREMENTS FOR SEGMENTAL INERTIA PARAMETERS

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All measurements in millimetres

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<th>Ribcage</th>
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<th>Shoulder</th>
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<th>Elbow</th>
<th>Forearm</th>
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### RIGHT ARM

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A3 - 11
A3.2 Example of subject MP file

{*ALL DISTANCE MEASUREMENTS IN millimeters, ALL ANGLES IN degrees*}

{*General Parameters*}

$StaticHeadLevel = 1
$StaticFootFlat = 1
$MuscleLengthsOutput = 0
$MarkerDiameter = 25
$HeadTilt = 0
$LateralShoulderOffset = 0
$FootThickness = 0
$LElbowWidth = 84
$RElbowWidth = 87
$WristThickness = 0
$HandThickness = 0
$StaticFootFlat = 1
$Bodymass = 77.1

{*VCM model-specific parameters*}

{*=---------------------------------=*

$LAsisTrocanterDistance = 0
$RAsisTrocanterDistance = 0
$LLegLength = 0
$RLegLength = 0
$LKneeWidth = 124
$RKneeWidth = 122
$LAnkleWidth = 74
$RAnkleWidth = 74

$LAnkleHeight = 74.2
$RAnkleHeight = 59.9
$LTibialTorsion = 0
$RTibialTorsion = 0
$LThighRotation = 0
$RThighRotation = 0
$LShankRotation = 0
$RShankRotation = 0

{*Deadband*}
{*======*=}
{*$Deadband controls the minimum angle (degrees) between segment definition
lines below which helical vector interpolation is employed. $Deadband is
disabled when creating .ASF files or when $Static parameter is set to 1*}
$Deadband = 10

{* Anthropometrics for subject based on model by Yeadon 1990 *}
{* table explanation
  1. the segment mass in kg (scalar)
  2. the location of the centre of mass in local coordinates (vector)
  3. inertia values as components of vector \{Mf,Mt,Ml\} i.e. Mx,My,Mz (vector) *}

$HeadMass = 4.75
$HeadMassLoc = \{0,0,73.3\}
$HeadInertia = \{24000,24000,14400\}

$ThoraxMass = 20.4282
$ThoraxMassLoc = \{0,0,106.8\}
$ThoraxInertia = \{353400,276500,219200\}

$AbdomenMass = 2.0809
$AbdomenMassLoc = \{0,0,-23\}
$AbdomenInertia = \{11000,6800,17000\}

$PelvisMass = 7.8846
$PelvisMassLoc = \{0,0,63.7\}
$PelvisInertia = \{60300,44400,79800\}

$LForearmMass = 1.731 {* this includes the hand ! *}

A3 - 13
\$L_{\text{Forearm Mass}} = 10,0,167.91
\$L_{\text{Forearm Inertia}} = \{24600,24700,1200\}

\$R_{\text{Forearm Mass}} = 1.8819
\$R_{\text{Forearm Mass Loc}} = \{0,0,162.61\}
\$R_{\text{Forearm Inertia}} = \{25600,25600,1400\}

\$L_{\text{Upper Arm Mass}} = 2.23
\$L_{\text{Upper Arm Mass Loc}} = \{0,0,122.7\}
\$L_{\text{Upper Arm Inertia}} = \{17700,17700,2700\}

\$R_{\text{Upper Arm Mass}} = 2.4461
\$R_{\text{Upper Arm Mass Loc}} = \{0,0,123.1\}
\$R_{\text{Upper Arm Inertia}} = \{18100,18100,3200\}

\$L_{\text{Femur Mass}} = 11.1534
\$L_{\text{Femur Mass Loc}} = \{0,0,174.6\}
\$L_{\text{Femur Inertia}} = \{164800,164800,46300\}

\$R_{\text{Femur Mass}} = 11.1293
\$R_{\text{Femur Mass Loc}} = \{0,0,175.6\}
\$R_{\text{Femur Inertia}} = \{167200,167100,45800\}

\$L_{\text{Tibia Mass}} = 4.7912
\$L_{\text{Tibia Mass Loc}} = \{0,0,186.1\}
\$L_{\text{Tibia Inertia}} = \{72700,72700,7600\}

\$R_{\text{Tibia Mass}} = 4.7025
\$R_{\text{Tibia Mass Loc}} = \{0,0,185.3\}
\$R_{\text{Tibia Inertia}} = \{69200,69200,7300\}

\$L_{\text{Foot Mass}} = 0.9165

A3 - 14
$\text{LFootMassLoc} = \{75.9,0,0\}$  
$\text{LFootInertia} = \{800,2900,2800\}$

$\text{RFootMass} = 0.9745$  
$\text{RFootMassLoc} = \{77,0,0\}$  
$\text{RFootInertia} = \{800,3100,3000\}$

{ joint centre locations expressed in relation to a coordinate frame in the parent based on Gamage & Lasenby 2002 *}  
$\text{PLHJC} = \{-8.3992886,-131.00078,46.52634\}$  
$\text{PRI-UC} = \{13.380746,125.77230,50.20582\}$  
$\text{PRSJC} = \{132.41203,139.50060,-145.6093\}$  
$\text{PLSJC} = \{136.41895,-133.97908,-145.52207\}$  
$\text{PREJC} = \{175.59352,6.9562303,61.909808\}$  
$\text{PLEJC} = \{187.74990,-16.522408,47.569820\}$

{ joint centre in relation to the segment they are on *}  
$\text{MLHJC} = \{6.10358,-117.606,25.4408\}$  
$\text{MRI-UC} = \{9.01168,95.8261,22.6941\}$  
$\text{MRSJC} = \{-20.7034,44.6433,69.4187\}$  
$\text{MLSJC} = \{32.9398,36.434,69.0348\}$  
$\text{MREJC} = \{-6.32144,-30.384,-4.41414\}$  
$\text{MLEJC} = \{-16.7373,40.7495,-6.14987\}$

{ markers on condyles so we can use point points? *}  
$\text{midpts} = 1$

{ logged midpoint joint centre in relation to the segment they are on *}  
$\text{GLKJC} = \{5.25703,-63.8173,-19.8622\}$  
$\text{GRKJC} = \{13.2717,60.6769,-19.7158\}$  
$\text{GLEJC} = \{4.25475e-017,44.8792,3.21978\}$  
$\text{GREJC} = \{-2.65922e-017,-48.7809,4.59637\}$

{*Static Trial Parameters*}
{*=================================================================*}

$\text{LegLength} = 943.107$

$\text{PelvisSize} = 213.47$

$\text{GPelvisSize} = 129.728$

$\text{LAnkleFlexOS} = 11.7786$

$\text{RAnkleFlexOS} = 9.90227$

$\text{LFootLength} = 206.205$

$\text{RFootLength} = 205.137$

$\text{ThoraxSize} = 153.271$

$\text{GThoraxSize} = 193.388$

$\text{HeadSize} = 163.879$

$\text{HeadFlexOS} = 36.1132$

$\text{IshoDist} = 311.484$

$\text{Height} = 1720$

$\text{GLAnkleFlexOS} = 11.7786$

$\text{GRAnkleFlexOS} = 9.90227$

$\text{GLFootLength} = 206.205$

$\text{GRFootLength} = 205.137$
This appendix contains information on a body of work completed as part of this PhD. The work was undertaken to investigate the precision with which functionally determined JCs can be estimated and implemented when analysing human athletic movement. It explains fully some of the arguments referred to in Chapters 2, 4 and 7. The work in this appendix was conducted in collaboration with M.T.G. Pain, PhD and M. Begon, PhD. It is hoped the findings of this investigation will be published in the near future.
INTRODUCTION

Human movement analysis is carried out on many scales, ranging from precise clinical joint analysis to technical analysis of explosive sporting movements. An initial step for analysing human movement is the determination of joint centre (JC) locations. Once JC locations have been determined a method of reconstructing them during the movement of interest is normally required. This involves expressing the JC location in terms of a local reference frame of markers on a segment.

The accuracy of functional methods in determining the optimised centres of rotation (OCR) has been tested using computer simulation models and/or rigid mechanical linkage devices (Ehrig et al., 2006; Camomilla et al., 2006; Piazza et al., 2001) and has been shown to approximate OCR to within 1 mm. Although noise is introduced in these models it is pertinent to explore how functional methods perform when implemented on actual human movement data. This has been done in only a few studies and only for the hip and shoulder joints (Monnet et al., in press; Leardini et al., 1999; Bao and Willems, 1999; Shea et al., 1997). Leardini’s group (1999) found that their functional method approximated the real JC obtained through roentgen stereophotogrammetric analysis better than predictive methods, 13 mm rather than 25 mm (Bell et al., 1990). Monnet’s group (2007) compared the SCoRE method (Ehrig et al., 2006) to the helical axis method in locating the glenohumeral joint in vivo and found the former to be more precise and unaffected by movement velocity. However, researchers have warned that implementing functional methods under ‘suboptimal’ conditions may lead to inaccurate estimation of the OCR (Piazza et al., 2004). Results depend on the type of movement used and the range of motion (RoM) of the joint (Begon et al. 2007; Camomilla et al., 2006; Siston and Delp, 2006). The RoM really needs to exceed 15° (Camomilla et al., 2006; Piazza et al., 2001) and a marked improvement in accuracy is obtained with a RoM above 20° or in some cases 45° (Ehrig et al., 2006). Further factors that affect the results are the sample number, the proximity of the marker centroid to the actual joint centre, the distance between markers (Camomilla et al., 2006) and the signal processing (Begon et al.; 2007; Chèze, 1995). The movements performed in the above in vivo experiments are limited to determining the JC. They do not explore the limitations of implementing and reconstructing the obtained JC during further movement analysis.
Much research has been done and is still ongoing to improve the accuracy of functional algorithms which determine OCR. However, there is a lack of research in whether the obtained locations can be used accurately and effectively when analysing subsequent human movement, especially where the noise from soft tissue deformation is substantially different from the trials used to determine the OCR. This will be particularly problematic during whole body athletic movements as a number of issues need to be considered. These include: ten-fifteen segments are required to represent the human body; too many markers can inhibit the movement; marker placement will need to be adjusted between subjects as musculature and movement technique may differ; the nature of the athletic movement will cause skin movement artefacts much greater than in simple movements used to approximate JC.

Once the JC have been determined the following procedures are commonly performed to allow the reconstruction of JC during the performance trials and each procedure has limitations associated with it. The OCR is expressed in terms of reference frames representing adjacent segments. These segments will normally be defined using at least three markers for each segment, if the segment motion is to be independently determined. The OCR is expressed as a constant vector in this local reference frame, which assumes that the segment is rigid. This assumption is obviously incorrect as the markers defining the segment will demonstrate movement artefacts (Reinschmidt, 1997; Capozzo, 1996; Karlsson, 1994; Woltring, 1991). Hence, the OCR location will be subject to the variability of the created reference system. This variability may be minimised by using more than three markers, and clusters of markers with optimisation procedures to minimise deformation, but cannot be eliminated fully (Challis, 1995; Andriacchi, 1998).

The first aim of this study is to obtain JC coordinates from human motion data using the SCoRE method (Ehrig et al., 2006) for the upper limb at both the shoulder and elbow and to assess to what degree these locations can be estimated in vivo. The second aim is to address potential issues with implementing these JC locations for the analysis of human movement during athletic activities. The second aim should illustrate that despite the theoretically high degree of accuracy of the functional method, the method of recalling the JC location will determine the final accuracy of any movement analysis during such activities.
METHODS

This study was divided into three parts. Part 1 determined JCs based on real human movement data. Part 2 investigated variability of marker combinations from Part 1 during a punch. Part 3 then investigated how the reconstruction of a chosen JC during a punch affected its position. All data were collected at 240 Hz. The algorithms used in each of these three parts are in Appendix 1.

One healthy male volunteer (age: 35; height: 1.75 m; weight: 92 kg), who had given informed consent in accordance with the university’s ethical advisory committee procedures took part in this study. The subject was fitted with six retro-reflective markers on each of the following segments: torso, (including the shoulder area), upper arm and forearm.

For Parts 1 and 2 all calculations were performed on the raw data and the same data which had undergone solidification using the method proposed by Chèze (1995). In Part 3 only solidified data were analysed.

**Part 1**

Set-up movement data were collected to determine the locations of the JC. The subject was instructed to perform slow movements over a large range of motion. For the shoulder joints, the subjects performed a star-arc movement (Camomilla et al., 2006). For the elbow, lower arm flexion, extension, pronation, supination and circumduction were performed. The shoulder and elbow set-up movements were acquired at 240 Hz but only every 4th sample was used to reduce the volume of data to 1480 and 1289 samples respectively. Groups of three markers that were used to define a local reference frame were called triads.

Multiple JCs were estimated from the set-up movement data using the SCoRE method (Ehrig et al., 2006) for all permutations of three from six markers in the proximal segment and three from six markers in the distal segment. The SCoRE method determines JC locations relative to each segment which are then combined to reconstruct JCs in the global frame, this yielded \( 6P_3 \times 6P_3 = 14,400 \) possible JC locations. All these solutions were reconstructed in a global frame for one time frame of the static trial. The radius of a sphere of 95% confidence and a mean JC location
were obtained by iteratively discarding outliers. As the SCoRE method of calculating the JC has been shown to be accurate in theoretical experiments (Ehrig et al., 2006), the sphere obtained in this step was termed a sphere of accuracy. Each triad had six permutations for the order of rotation and hence six JCs. Combining a single triad from the proximal segment with a single triad from the distal segment gave 36 JCs per triad combination, and $^6C_3 \times ^6C_3 = 400$ combinations. For each of the 400 triad combinations the 36 JC locations per triad pair were fitted with individual spheres of accuracy.

Part 2
In this step the kinematics of a punch were measured in order to establish if different marker sets performed differently during a dynamic movement. The 36 JC locations associated with each of the 400 triad combinations were calculated for each frame of the punch and were fitted with a 95% sphere of precision. The maximal radius of each sphere of precision obtained during the punch was recorded and then the combination of the proximal and distal triads which resulted in the sphere with the lowest maximal radius was determined. The results of this step could suggest which markers should be used in Part 1 to obtain the most robust estimation of the JC based on the specific athletic activity under investigation.

Part 3
This part aimed to evaluate the errors in JC reconstruction which were associated with triad deformation during two phases of the punch, punch motion (185 samples) and punch impact (65 samples). Three coordinate systems that were as independent as possible but had given good results in Part 2 were selected. The JC location calculated in one of the three triads ($S_1$, $S_2$ or $S_3$) was expressed in turn in the other two triads. During the punch the change in the vector between the JC and the origin of the two coordinate systems that had not defined the JC was calculated. The maximal change in this vector was an indicator of the error, $e_i$, in the JC location during the trial. If the segments were rigid and there was no noise, these values should remain constant. This resulted in three simultaneous equations relating error measured in one coordinate system relative to another coordinate system. The three measured error indicators are given by the following equations in which $a$, $b$ and $c$ are the errors associated with $S_1$, $S_2$ and $S_3$ respectively.
Solving these for the measured error values gives the error associated with each coordinate system.

The error in JC location had to be determined in this way for the following reasons. Firstly, due to the measured motion being caused by the true movement of the segment and the movement artefact of the markers an absolute comparison cannot be made and local systems need to be used. In each local system, the local JC vector was constant but all local coordinate frames deformed and moved during the punch and hence the location of JC vectors relative to the segment would vary but not with respect to their origins. Errors in the real JC location relative to the system origin are not expressible in that system even though they exist. These errors can only be noticed by their effect on markers not of their system, but these other markers also have their own errors associated with them. A description of the change between the two independent frames could illustrate the variability of the JC position.

RESULTS

Part 1

The spheres of accuracy for the shoulder and elbow joints are shown in Figure 1. These clouds of points are made up of overlapping clusters of points relating to the 95% of the 400 triad pairs. As outlined earlier, the JC were reconstructed with solidification (WS) and without solidification (WOS). Table I shows the mean x, y, z location of the centre of the sphere for all the JCs and the mean x, y, z location for the best nine JCs. The radius of the best nine WOS was 12 mm and the dispersion, as described by the SD, of the best nine JCs was around 10 mm. Table I also shows that although solidification may lower the radii of the best triads, it disperses them more in space as Figure 2 demonstrates.

Table I around here

The maximum radii of the spheres of accuracy for the 400 JC locations determined without solidification for the shoulder in the static position are shown in Table 2.
Figure 3 graphically represents the data format of Table 2 using a 20 by 20 greyscale coded grid; white represents 0 mm and black represents 60 mm. The radii for both the shoulder and the elbow, with and without solidification, are presented in Figure 3. The centre of the cloud of JCs and the best individual triad JCs, based on radius were close:

*** Figure 1 to go near here***
*** Figure 2 to go near here***
*** Table 2 to go near here***
***Figure 3 to go near here***

Part 2
The spheres of precision for the shoulder and elbow joints are shown in Figure 4. The maximum radii of the spheres of precision of the 36 JC locations throughout the punch are shown in Figure 5 (same graphical parameters as Figure 3). During the punch the maximum radii for the shoulder ranged from 13.5 to 43.3 mm WOS and from 6.2 to 24.6 mm WS; the maximum radii for the elbow ranged from 14.0 to 55.6 mm WOS and from 3.0 to 23.8 mm WS. The best ten triad pairings are in Table 3 and show that not all triads that performed well in Part 1 did so in Part 2.

*** Figure 4 and 5 to go near here ***
*** Table 3 to go near here ***

Part 3
The errors associated with the different co-ordinate systems are shown in Table 4. The table shows the errors per marker set on the proximal and the distal segment for punch motion and punch impact and only for WS. For the shoulder the errors range from 2.5 to 13.8 mm for the punch motion and from 8.2 to 31.2 mm for the punch impact. For the elbow the errors range from 1.5 to 21.1 mm for the punch motion and from 4.8 to 72.4 mm for the punch impact.

*** Table 4 to go near here ***
DISCUSSION

Although the functional methods by Ehrig et al (2006) have produced very accurate results in estimating JC in theory (< 1mm), additional problems introduced and further steps required when determining and utilising JC with human movement data decreased this accuracy considerably. Part 1 involved determining the JC locations but nowhere near the accuracy reported by Ehrig et al (2006) was possible even using the most optimistic results from this study. The radii of the spheres of all the points includes triads which would be expected to perform poorly so gives an unrealistic worst case scenario for the spread of possible JCs. Ninety-five percent of a population lies within two SD, and the SD of the mean JC of the best nine JCs was 10 mm. Combining this with the diameter of an individual triad’s JCs being 24mm, these results would indicate that determining the JC with an accuracy of greater than 20 mm is unlikely. This value is more comparable with the 13 mm RMS error found by Leardini et al. (1999) in the location of the hip JC using functional methods with a stereophotogrammetric reference.

Although radii, r, in Table 1 are lower with solidification they have limited importance in Part 1 as they only illustrates the precision of each individual group of JCs for a triad, not how well they group together about a single point in space. Hence it does not give any information about whether there may be a degree of consistency in finding a real point that is comparable to the real JC. In fact for both the shoulder and the elbow although precision increased the spread of the JCs in space for the well behaved triads was worse. Solidification has reduced random error but has dispersed the precise groups further apart, especially along one axis of the elbow. This is likely to be a result of systematic errors introduced from skin movement artefact which is not random but has its own coherent structure (Pain and Challis, 2002) and is often correlated with the whole limb motion (Woltring, 1991). The elbow exhibited this effect more severely than the shoulder. The elbow was modelled as a ball-and-socket joint, but the results are all distributed along an axis and solidification dispersed JCs along this axis. Proximal markers on the forearm will not have included sufficient pronation-supination information and hence resulted in JC locations on the axis of rotation.
In order to choose the optimal marker set for the athletic activity which is to be studied, this paper suggests conducting a pilot study in which the athletic movement is studied carefully to obtain a sphere of precision for various marker triads. One of the triads yielding the smallest radii should hence be chosen to conduct the set-up movements to determine the JC for this particular activity. It was not expected that the best triads found in Part 2 would always be the same as the best triads found in Part 1 since the movement artefact of the markers in the set-up movements was unlikely to be the same as that in the actual dynamic activity. This is confirmed by the results. The best spheres of accuracy and precision are often based on the same markers but not always. For Parts 2 and 3 using solidification to determine the spheres of precision was a great benefit as a triad that did not vary during the movement is required to accurately determine whatever location has been defined as the JC.

After having determined the JC in terms of a marker set that does not vary excessively during the activity, it was important to quantify how reliable this location was during the activity. Hence, the JC – triad origin vector was compared in two other coordinate systems and simultaneous equations were solved to give an indicator of the error of each coordinate system in which the JC could be reconstructed and this was done for a few different triads. Reconstructing a JC from a single set of markers is likely to adversely affect the results. The same markers on a segment tend to perform well. Hence, it is difficult to pick good triads which are completely independent. It should also be noticed that different triads performed well during the movement and impact phase of the punch, hence highlighting the soft tissue motion dependence. The implementation of a solidification procedure makes a marked difference.

In conclusion, this research suggests that markers used to determine the JC using the functional method should be chosen specifically for the activity under investigation. The best accuracy obtained in JC determination will not be as accurate as that found in theoretical settings and will be on the order of tens of millimetres. Further inaccuracies on the order of a few to tens of millimetres will be introduced by the reconstruction of the estimated JC due to marker motion used to define the JC during the activities.
REFERENCES


APPENDICES

Part 1:

Purpose:

1. Calculate JC with Ehrig (2006)'s functional method from all the combinations of three markers among six fixed on the proximal segment and three among six on the distal segment. The location is calculated in both local coordinate systems.

2. Calculate the radii of the sphere of accuracy for each couple of proximal/distal triads in the global coordinate system for a static posture.

Input:

P (*Positions of the 12 markers in the global frame during the set-up*)
S (*Positions of the 12 markers in the global frame during the static posture*)

Output: CoR (*Joint centre locations*), r1 (*radii of the spheres of accuracy*)

BEGIN

FOR i (*triad of the proximal segment*) ← 1 to 20
   M1 ← SelectMarkers(P, i)
FOR k (*triad of the distal segment*) ← 1 to 20
   M2 ← SelectMarkers(P, k)
   FOR j (*Coordinate system of the triad i*) ← 1 to 6
      R1 ← RotationMatrix(M1, j)
      FOR l (*Coordinate system of the triad k*) ← 1 to 6
         R2 ← RotationMatrix(M2, l)
         \( \text{jC}^{ij}_{kl} \leftarrow \text{LocalCoR}(M1, M2, R1, R2) \)
         CoR^{ij}_{kl} ← GlobalCoR(\( \text{jC}^{ij}_{kl} \), \( \text{kC}^{ij}_{kl} \), S)
      ENDFOR
   ENDFOR
ENDFOR

r1_{kl} ← SphereRadius(CoR^{ij}_{kl})

ENDFOR

END
Part 2:

Purpose:

Calculate the maximal radii of the spheres of precision for each couple of proximal/distal triads in the global coordinate system during an athletic movement.

Input:

C (*Centre of rotation locations in all the local frames (Part 1)*)
M (*Positions of the 12 markers in the global frame during the athletic movement*)

Output: r2 (*maximal radii of the sphere of precision*)

BEGIN

FOR i (*triad of the proximal segment*) ← 1 to 20
FOR k (*triad of the distal segment*) ← 1 to 20
FOR j (*Coordinate system of the triad i*) ← 1 to 6 [J]
FOR l (*Coordinate system of the triad k*) ← 1 to 6 [K]
FOR t (*samples of the punch*) ← 1 to T

CoR_{ij_{kl}}(t) ← GlobalCoR_{ij}C_{ik}, klC_{ik}, M)

ENDFOR
ENDFOR

r'_{ik} ← SphereRadius(CoR_{ij_{kl}}(t))

r2'_{ik} ← max(r'_{ik})

ENDFOR
ENDFOR
END
Part 3:
Purpose:
Calculate the variability of the JC location during an athletic movement due to proximal (or distal) triad deformation for the three best and as independent as possible triads that were defined in Part 2:
1. Express the JC calculated from one triad in the other two triads for the punch before and during impact
2. Calculate the maximal distance between the JC vector relative to the average vector
3. Solve a linear system to determine the error associated to the three triads

Algorithm for the proximal segment

Input:
C (*Centre of rotation locations in local frame for 3 proximal and 3 distal triads (Part 1)*)
S (*Markers positions in the global frame during the static posture*)
M1 (*Markers positions in the global frame before impact*)
M2 (*Markers positions in the global frame during the impact*)

Output:
L1 (*maximal change in position of the JC before impact*)
L2 (*maximal change in position of the JC during the impact*)
E1 (*error due to triad deformation before impact *)
E2 (*error due to triad deformation during impact*)

BEGIN
FOR i (*best triad for the proximal segment*) ← 1 to 3 [I]
  FOR i2 (*other best triad for the proximal segment*) ← 1 to 3 [I2]
    FOR j (*Coordinate system of the triad i*) ← 1 to 6 [J]
      mCoR$^j$ ← $MeanLocalCoR(\Sigma^{ij}_{KL}, \Sigma^{ij}_{KL}, S)$
FOR $t$ (*samples before impact*) ← 1 to $T_1$
\[ C_{OR1}^{ij}(t) \leftarrow \text{GlobalCoR}(m_{CoR}^{ij}, M_1) \]
ENDFOR

FOR $t$ (*samples during impact*) ← 1 to $T_2$
\[ C_{OR2}^{ij}(t) \leftarrow \text{GlobalCoR}(m_{CoR}^{ij}, M_2) \]
ENDFOR

FOR $j_2$ (*Coordinate system of the triad $i_2$*) ← 1 to 6 [J2]

FOR $t$ (*samples before impact*) ← 1 to $T_1$
\[ C_{OR1}^{ij}^{i_2j_2}(t) \leftarrow \text{LocalCoR}(C_{OR1}^{ij}, M_1) \]
ENDFOR

FOR $t$ (*samples during impact*) ← 1 to $T_2$
\[ C_{OR2}^{ij}^{i_2j_2}(t) \leftarrow \text{LocalCoR}(C_{OR2}^{ij}, M_2) \]
ENDFOR

\[ i_2D_1^{i_2j_2} \leftarrow \text{DistanceToAverage}(C_{OR1}^{i_2j_2}_{KL}) \]
\[ i_2D_2^{i_2j_2} \leftarrow \text{DistanceToAverage}(C_{OR2}^{i_2j_2}_{KL}) \]
ENDFOR
ENDFOR

\[ i_2L_1^{i_2} \leftarrow \text{MaxError}(i_2D_1^{i_2j_2}) \]
\[ i_2L_2^{i_2} \leftarrow \text{MaxError}(i_2D_2^{i_2j_2}) \]
ENDFOR
ENDFOR

\[ E_1 \leftarrow \text{SolveLinearEq}(i_2L_1^{i_2}) \]
\[ E_2 \leftarrow \text{SolveLinearEq}(i_2L_2^{i_2}) \]
END
List of figures

Figure 1: Upper views of the upper limb and the 14,400 locations of shoulder and elbow joint centres (in black dots) without solidification [a] and with solidification [b]. The bodies are from the left to the right: trunk, shoulder, upper-arm and lower arm.

Figure 2: A 3D representation of the dispersion of the best triads for the elbow JC (black) [a] without solidification and [b] with solidification.

Figure 3: Radii of the sphere of accuracy (static position) for the elbow and the shoulder with (w solid.) and without (wo solid.) solidification. Note: the linear colour code represents the radius (white=0 mm and black=60 mm). The bottom left figure (Shoulder wo solid.) is a representation of Table 2. The results were sorted in rows and columns according to the average value of the proximal and distal triads. This means the bottom left figure 1 is equal to the top left of Table 2.

Figure 4: Lateral views of the upper limb and the 14,400 locations of shoulder and elbow joint centres without solidification [a] and with solidification [b] for the 1st frame (black lines and dots) and the 220th frame (grey lines and dots) of the punch.

Figure 5: Radii of the sphere of precision (during the movement) for the elbow and the shoulder with (w solid.) and without (wo solid.) solidification. Note: the linear colour code represents the radius (white=0 mm and black=60 mm). The results were sorted in rows and columns according to the average value of the proximal and distal triads.
Table 1. Mean x, y, z location of the centre of the sphere for all the JCs and the mean x, y, z location for the best nine JCs for the shoulder and elbows. a – with solidification and b – without solidification.

### Without Solidification (mm)

<table>
<thead>
<tr>
<th></th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>691.5</td>
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<tr>
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<td>z</td>
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<td>r</td>
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<td>All points</td>
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<tr>
<td>Mean, best 9 Ts</td>
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<td>Elbow</td>
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<tr>
<td>Shoulder</td>
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### With Solidification (mm)

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<th>Shoulder</th>
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</thead>
<tbody>
<tr>
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<td>z</td>
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<td>-----</td>
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Note: The local frames were calculated with markers M1, M2 and M3. M1-M2-M3 defined the x-vector and M1-M2-M3 was the plane of reference.

The triads were sorted according to the average value of the sphere of accuracy.
Table 3: Radii [mm] of the *spheres of precision* for the ten best triads for the shoulder, without solidification. For each couple of proximal - distal triads, the sphere includes 95% of the 36 joint centre locations.

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<td>19.8</td>
<td>20.6</td>
<td>21.5</td>
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</tbody>
</table>
Table 4: Indicators of error in the joint centre ([a] shoulder and [b] elbow) reconstruction due to the triad deformation during the movement and the impact for the proximal and the distal segments. (T = triad)

<table>
<thead>
<tr>
<th>Precision</th>
<th>Markers</th>
<th>Movement (mm)</th>
<th>Impact (mm)</th>
</tr>
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<tbody>
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<tr>
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<tr>
<td>SHOUL.</td>
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<tr>
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<td>T4</td>
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</tr>
<tr>
<td></td>
<td>T1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>U. ARM</td>
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<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>ELBOW JC with solidification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>U. ARM</td>
<td>T4</td>
<td>1</td>
<td>3</td>
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<tr>
<td></td>
<td>T7</td>
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<td></td>
<td>T1</td>
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<td>L. ARM</td>
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<td>4</td>
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<td></td>
<td>T3</td>
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Figure 1: Upper views of the upper limb and the 14,400 locations of shoulder and elbow joint centres (in black dots) without solidification [a] and with solidification [b]. The bodies are from the left to the right: trunk, shoulder, upper-arm and lower arm.
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Note: the linear colour code represents the radius (white=0 mm and black=60 mm). The bottom left figure (Shoulder wo solid.) is a representation of Table 2. The results were sorted in rows and columns according to the average value of the proximal and distal triads. This means the bottom left figure 1 is equal to the top left of Table 2.
Figure 4: Lateral views of the upper limb and the 14,400 locations of shoulder and elbow joint centres without solidification [a] and with solidification [b] for the 1st frame (black lines and dots) and the 220th frame (grey lines and dots) of the punch.
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Note: the linear colour code represents the radius (white=0 mm and black=60 mm). The results were sorted in rows and columns according to the average value of the proximal and distal triads.
This appendix contains the photos taken of all subjects fitted with markers for the TKD and karate data collections.
A.5.1. TKD subjects:

TKD1

TKD2
A.5.2. KAR subjects:

KAR1

KAR2
This appendix contains all the mean and standard deviation moment time histories for both execution modes for the three TKD kicks and the karate kick. The curves are presented in the following order with joints in proximal-distal order for limbs; and top to bottom for central segments:

- Kicking leg
- Non-kicking leg
- Central segments

For karate the moments of the arm are also included and presented in the following order:

- Front arm
- Back arm

Moments are presented in x, y, z order, i.e. moments about the frontal, lateral, and longitudinal axis. For axis definitions refer to § 4.4.6.
TKD1 Kick 1 – joint moments of the legs
TKD1 Kick 1 – joint moments of the central segments
TKD1 Kick 2 – joint moments of the legs

TKD1 K2 Right Hip X  
TKD1 K2 Right Hip Y  
TKD1 K2 Right Hip Z

TKD1 K2 Right Knee X  
TKD1 K2 Right Knee Y  
TKD1 K2 Right Knee Z

TKD1 K2 Left Hip X  
TKD1 K2 Left Hip Y  
TKD1 K2 Left Hip Z

TKD1 K2 Left Knee X  
TKD1 K2 Left Knee Y  
TKD1 K2 Left Knee Z
TKD1 Kick 2 – joint moments of the central segments

TKD1 R2 Neck X

TKD1 R2 Neck Y

TKD1 R2 Neck Z

TKD1 K2 Upper Back X

TKD1 K2 Upper Back Y

TKD1 K2 Upper Back Z

TKD1 K2 Lower Back X

TKD1 K2 Lower Back Y

TKD1 K2 Lower Back Z
TKD1 Kick 3 - joint moments of the legs

TKD1 K3 Left Hip X
TKD1 K3 Left Hip Y
TKD1 K3 Left Hip Z

TKD1 K3 Left Knee X
TKD1 K3 Left Knee Y
TKD1 K3 Left Knee Z

TKD1 K3 Right Hip X
TKD1 K3 Right Hip Y
TKD1 K3 Right Hip Z

TKD1 K3 Right Knee X
TKD1 K3 Right Knee Y
TKD1 K3 Right Knee Z
TKD1 Kick 3 – joint moments of the central segments
TKD2 Kick 1 – joint moments of the legs

TKD2 K1 Left Hip X
TKD2 K1 Left Hip Y
TKD2 K1 Left Hip Z

TKD2 K1 Left Knee X
TKD2 K1 Left Knee Y
TKD2 K1 Left Knee Z

TKD2 K1 Right Hip X
TKD2 K1 Right Hip Y
TKD2 K1 Right Hip Z

TKD2 K1 Right Knee X
TKD2 K1 Right Knee Y
TKD2 K1 Right Knee Z
TKD2 Kick 1 – joint moments of the central segments
TKD2 Kick 2 – joint moments of the legs
TKD2 Kick 2 – joint moments of the central segments
TKD2 Kick 3 – joint moments of the legs

TKD2 K3 Left Hip X
TKD2 K3 Left Hip Y
TKD2 K3 Left Hip Z

TKD2 K3 Left Knee X
TKD2 K3 Left Knee Y
TKD2 K3 Left Knee Z

TKD2 K3 Right Hip X
TKD2 K3 Right Hip Y
TKD2 K3 Right Hip Z

TKD2 K3 Right Knee X
TKD2 K3 Right Knee Y
TKD2 K3 Right Knee Z

A6 - 12
TKD2 Kick 3 – joint moments of the central segments
TKD3 Kick 1 – joint moments of the legs

TKD3 KI Left Hip X  TKD3 KI Left Hip Y  TKD3 KI Left Hip Z

TKD3 KI Left Knee X  TKD3 KI Left Knee Y  TKD3 KI Left Knee Z

TKD3 KI Right Hip X  TKD3 KI Right Hip Y  TKD3 KI Right Hip Z

TKD3 KI Right Knee X  TKD3 KI Right Knee Y  TKD3 KI Right Knee Z
TKD3 Kick 1 – joint moments of the central segments
TKD3 Kick 2 – joint moments of the legs

TKD3 K2 Right Hip X

TKD3 K2 Right Hip Y

TKD3 K2 Right Hip Z

TKD3 K2 Right Knee X

TKD3 K2 Right Knee Y

TKD3 K2 Right Knee Z

TKD3 K2 Left Hip X

TKD3 K2 Left Hip Y

TKD3 K2 Left Hip Z

TKD3 K2 Left Knee X

TKD3 K2 Left Knee Y

TKD3 K2 Left Knee Z

A6 - 16
TKD3 Kick 2 – joint moments of the central segments
TKD3 Kick 3 – joint moments of the legs
TKD3 Kick 3 – joint moments of the central segments
TKD4 Kick 1 – joint moments of the legs
TKD4 Kick 1 – joint moments of the central segments

TKD4 K1 Neck X
TKD4 K1 Neck Y
TKD4 K1 Neck Z

TKD4 K1 Upper Back X
TKD4 K1 Upper Back Y
TKD4 K1 Upper Back Z

TKD4 K1 Lower Back X
TKD4 K1 Lower Back Y
TKD4 K1 Lower Back Z
TKD4 Kick 2 – joint moments of the legs
TKD4 Kick 2 – joint moments of the central segments
TKD4 Kick 3 – joint moments of the legs

TKD4 K3 Left Hip X

TKD4 K3 Left Hip Y

TKD4 K3 Left Hip Z

TKD4 K3 Left Knee X

TKD4 K3 Left Knee Y

TKD4 K3 Left Knee Z

TKD4 K3 Right Hip X

TKD4 K3 Right Hip Y

TKD4 K3 Right Hip Z

TKD4 K3 Right Knee X

TKD4 K3 Right Knee Y

TKD4 K3 Right Knee Z
TKD4 Kick 3 – joint moments of the central segments
TKD5 Kick 1 – joint moments for the legs
TKD5 Kick 1 – joint moments for the central segments
TKD5 Kick 2 – joint moments of the legs
TKD5 Kick 2 – joint moments of the central segments
TKD5 Kick 3 – joint moments of the legs

TKD5 K3 Left Hip X
TKD5 K3 Left Hip Y
TKD5 K3 Left Hip Z

TKD5 K3 Left Knee X
TKD5 K3 Left Knee Y
TKD5 K3 Left Knee Z

TKD5 K3 Right Hip X
TKD5 K3 Right Hip Y
TKD5 K3 Right Hip Z

TKD5 K3 Right Knee X
TKD5 K3 Right Knee Y
TKD5 K3 Right Knee Z
TKD5 Kick 3 – joint moments of the central segments

TKD5 K3 Neck X
TKD5 K3 Neck Y
TKD5 K3 Neck Z

TKD5 K3 Upper Back X
TKD5 K3 Upper Back Y
TKD5 K3 Upper Back Z

TKD5 K3 Lower Back X
TKD5 K3 Lower Back Y
TKD5 K3 Lower Back Z
KARI – joint moments of the legs

KARI K Left Hip X

KARI K Left Hip Y

KARI K Left Hip Z

KARI K Left Knee X

KARI K Left Knee Y

KARI K Left Knee Z

KARI K Right Hip X

KARI K Right Hip Y

KARI K Right Hip Z

KARI K Right Knee X

KARI K Right Knee Y

KARI K Right Knee Z
KAR1 – joint moments of the central segments
KARI - joint moments of the arms
KAR2 – joint moments of the legs
KAR2 – joint moments of the central segments
KAR2 - joint moments of the arms
KAR3 – joint moments of the legs
KAR3 – joint moments of the central segments
KAR3 – joint moments of the arms
KAR4 – joint moments of the legs
KAR4 – joint moments of the central segments
KAR4 – joint moments of the arms

KAR4 K Left Shoulder X
KAR4 K Left Shoulder Y
KAR4 K Left Shoulder Z

KAR4 K Left Elbow X
KAR4 K Left Elbow Y
KAR4 K Left Elbow Z

KAR4 K Right Shoulder X
KAR4 K Right Shoulder Y
KAR4 K Right Shoulder Z

KAR4 K Right Elbow X
KAR4 K Right Elbow Y
KAR4 K Right Elbow Z
KAR5 – joint moments of the legs
KAR5 - joint moments of the central segments