Technique in overarm throwing

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TECHNIQUE IN OVERARM THROWING

by

NURHIDAYAH OMAR

A doctoral thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

School of Sport, Exercise and Health Sciences
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ABSTRACT

Technique in Overarm Throwing

Nurhidayah Omar, Loughborough University, 2016

A computer simulation model of overarm throwing was developed to gain an understanding of the mechanics of overarm throwing and applied to fastball pitching. The movement was modelled as a three-dimensional system using eight rigid segments, with torque generators for upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper arm external/internal rotation. The baseball was attached at the distal end of the hand segment using a linear spring. The model was personalised to a pitcher so that simulation outputs could be compared with the pitcher’s performance. Kinematic data of overarm pitching were obtained using a Vicon Motion Analysis System and maximal voluntary joint torques were estimated using average maximal voluntary joint torques from previous studies. A torque-driven model was used to determine a specific set of maximal voluntary joint torques by varying $T_o$ while matching three performances concurrently. The torque-driven model was successfully evaluated, and shown to produce realistic movements, with mean overall differences between simulations and performances of 13% for three trials. The model was applied to further the understanding of the mechanics of overarm throwing. Optimising the technique of the pitcher with the simulation model increased the ball speed by 14% with more upper trunk flexion, scapula internal rotation and right upper arm external rotation used. The optimised technique showed proximal-to-distal sequencing, and increasing strength by 5% gave a slight improvement in performance of 0.6%. Varying strength by $\pm 30\%$ resulted in an increase of 2.7% in ball speed although not all joints used the 30% increase in strength. In summary, although increasing strength resulted in an increase in ball speed, technique variables such as upper trunk flexion and upper arm external rotation are arguably the most important factors for throwing fast.
LIST OF PUBLICATIONS

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To all my loved ones especially the One & Only
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................... ii
LIST OF PUBLICATIONS .................................................................................. iii
ACKNOWLEDGEMENTS ...................................................................................... iv
TABLE OF CONTENTS ......................................................................................... vi
LIST OF TABLES .................................................................................................. x
LIST OF FIGURES ................................................................................................. xii

## CHAPTER 1  INTRODUCTION ....................................................................... 1

1.1 Introduction ..................................................................................................... 1
1.2 The Area of Study .......................................................................................... 1
1.3 Problem Statement ......................................................................................... 2
1.4 Statement of Purpose ..................................................................................... 4
1.5 Research Questions ......................................................................................... 4
1.6 Chapter Organisation ....................................................................................... 6

## CHAPTER 2  LITERATURE REVIEW ............................................................ 7

2.1 Chapter Overview .......................................................................................... 7
2.2 Throwing Background .................................................................................. 7

### 2.2.1 Pitching Grips ...................................................................................... 8

#### 2.2.1.1 Four-seam Fastball ................................................................. 9
#### 2.2.1.2 Two-seam Fastball ................................................................. 10

### 2.2.2 Phases of Pitching ................................................................................ 11

#### 2.2.2.1 Wind-up ..................................................................................... 12
#### 2.2.2.2 Early Cocking/Stride ............................................................... 13
#### 2.2.2.3 Late Cocking ........................................................................... 15
#### 2.2.2.4 Acceleration ............................................................................. 16
#### 2.2.2.5 Deceleration ............................................................................. 17
#### 2.2.2.6 Follow-through ........................................................................ 17

2.3 Previous Experimental and Theoretical Studies ........................................ 17

### 2.3.1 Contribution of Segment rotations to Ball Velocity ......................... 17

#### 2.3.1.1 Lower Extremity ................................................................. 18
#### 2.3.1.2 Pelvis, Trunk and Shoulder Complex ................................... 20
2.3.1.3 Throwing Arm .............................................. 22
2.3.1.4 Non-throwing Arm ....................................... 25
2.3.2 Pitching Mechanics ........................................... 25
  2.3.2.1 Comparative Studies ..................................... 26
  2.3.2.2 Proximal-to-Distal Sequential Motion and Timing
          Window .......................................................... 28
  2.3.2.3 Mound vs Flat-ground Pitching .......................... 33
2.3.3 Three-dimensional Computer Simulation Models ............. 34
2.4 Summary of Literature ............................................... 39

CHAPTER 3 KINEMATIC ANALYSIS ............................................ 40
  3.1 Introduction ....................................................... 40
  3.2 Data Collection ................................................... 40
    3.2.1 Data Collection Set-up ................................... 41
  3.3 Protocol .............................................................. 44
  3.4 Anthropometric Measurements .................................. 44
  3.5 Segmental Motion Analysis ...................................... 44
  3.6 Splining the Data .................................................. 50
  3.7 Discussion ........................................................... 54
  3.8 Summary ............................................................. 54

CHAPTER 4 DEVELOPMENT OF ANGLE-DRIVEN SIMULATION
          MODEL ............................................................... 55
  4.1 Introduction ....................................................... 55
  4.2 General Description of the Eight-Segment Angle-Driven Model .... 55
  4.3 Inertia Parameters ............................................... 59
    4.3.1 Body Segmental Inertia Parameters .......................... 59
  4.4 Modelling the contact between the hand and ball .................. 60
    4.4.1 Position of the ball ......................................... 61
    4.4.2 Determination of ball release ............................... 62
  4.5 Cardan-Euler Angles .............................................. 63
    4.5.1 Joint Angular Velocity and Acceleration of Cardan-Euler Joint
          Angles .......................................................... 65
  4.6 Equations of Motion ............................................... 67
    4.6.1 Customisation of the Simulation Model ...................... 68
  4.7 Evaluation of the Angle-Driven Model ................................ 68
    4.7.1 Method to Evaluate the Angle-Driven Model ................. 68
LIST OF TABLES

Table 4.1: Segmental inertia parameters calculated from the inertia model .... 60
Table 4.2: Comparison of ball speed at release in each direction and the resultant for each trial (Exp: performance; Sim: angle-driven model) .... 71
Table 4.3: Root Mean Square Error (in meter) of the displacement of the distal end of each segment for Trial 3, Trial 4, Trial 5, Trial 6 and Trial 9 ................................................................. 72
Table 4.4: Root Mean Square Error (in meter) of the displacement of the distal end of each segment for Trial 10, Trial 13, Trial 14, Trial 16 and Trial 18 ................................................................. 73
Table 4.5: Root Mean Square Error (in meter) of the displacement of the distal end of each segment for Trial 19, Trial 20, Trial 23, Trial 25 and Trial 26 ................................................................. 74
Table 4.6: The mean differences of ball speed when each orientation of pelvis, upper trunk and right upper arm were kept constant .............. 86
Table 4.7: The mean differences of ball speed when each orientation of the right forearm, right hand, scapula, left upper arm and left forearm were kept constant ................................................. 87
Table 5.1: The seven parameters defining an activation profile ................. 93
Table 5.2: Initial estimate of torque – angular velocity profile for upper trunk ................................................................................................. 99
Table 5.3: Initial estimate of torque – angular velocity profile for upper arm ................................................................................................. 99
Table 5.4: Initial estimate of torque – angular velocity profile for scapula and forearm ............................................................................ 100
Table 5.5: An adjusted set of torque – angular velocity profile for upper trunk ................................................................................................. 102
Table 5.6: An adjusted set of torque – angular profile for upper arm ....... 102
Table 5.7: An adjusted set of torque – angular velocity profile for scapula and forearm ............................................................................ 103
Table 6.1: Joint/Segment movements and corresponding torque activation profiles .......................................................................................... 107
Table 6.2: RMS differences between performances and matched simulation from three trials ................................................................. 109
Table 6.3: Joint/Segment movements and corresponding torque activation profiles .......................................................................................... 114
Table 6.4: Limits of range-of-motion of the joints/segments (measured in °). 115
Table 6.5: RMS differences between model with elbow angle-driven and model with elbow torque-driven ................................................................. 116
Table 6.6: Ten parameters defining activation profile .............................. 117
Table 6.7: RMS differences between model with seven-parameter and model with ten-parameter activation profile .............................................. 119
Table 7.1: Comparison of the To values .................................................. 143
Table G1: Seven parameter values for upper trunk flexion obtained from previous studies ......................................................................................... 235
Table G2: Seven parameter values for upper trunk extension obtained from previous studies ................................................................................... 236
Table G3: Seven parameter values for upper trunk external rotation obtained from previous studies ................................................................. 236
Table G4: Seven parameter values for upper trunk internal rotation obtained from previous studies ................................................................. 237
Table G5: Seven parameter values for scapula external rotation obtained from previous studies ................................................................. 237
Table G6: Seven parameter values for scapula internal rotation obtained from previous studies ................................................................. 238
Table G7: Seven parameter values for upper arm flexion obtained from previous studies ......................................................................................... 238
Table G8: Seven parameter values for upper arm extension obtained from previous studies ......................................................................................... 239
Table G9: Seven parameter values for upper arm adduction obtained from previous studies ......................................................................................... 239
Table G10: Seven parameter values for upper arm abduction obtained from previous studies ......................................................................................... 240
Table G11: Seven parameter values for upper arm internal rotation obtained from previous studies ................................................................. 240
Table G12: Seven parameter values for upper arm external rotation obtained from previous studies ................................................................. 241
Table G13: Seven parameter values for forearm flexion obtained from previous studies ......................................................................................... 241
Table G14: Seven parameter values for forearm extension obtained from previous studies ......................................................................................... 242
Table G15: Seven parameter values for forearm pronation obtained from previous studies ......................................................................................... 242
Table G16: Seven parameter values for forearm supination obtained from previous studies ......................................................................................... 243
Table H1: Description of marker placement for data collection .................... 244
LIST OF FIGURES

Figure 2.1: Four-seam fastball grip (adapted from www.thecompletepitcher.com). .................................................................9
Figure 2.2: Marker location (adapted from Alaways and Hubbard, 2001). The ball on the left is in the two-seam configuration and the ball on the right is in the four-seam configuration. ..........................................9
Figure 2.3: Four-seam and two-seam spin direction (adapted from Kensrud et al., 2015). ..............................................................10
Figure 2.4: Two-seam fastball grip (adapted from www.thecompletepitcher.com). ........................................................................10
Figure 2.5: Sequence of motion in baseball pitch for a right-handed pitcher (adapted from Feltner and Dapena, 1986). .......................12
Figure 2.6: The stride and foot placement (adapted from Fleisig et al., 2009). ........................................................................15
Figure 3.1: The fastball pitching action .................................................................................................................................40
Figure 3.2: Schematic of experimental set-up; light grey arrows represent Vicon cameras and dark grey arrows represents video camera (figure not drawn to scale). ........................................................................42
Figure 3.3: Subject with retro-reflective markers .....................................................................................................................43
Figure 3.4: Ball with reflective markers .................................................................................................................................43
Figure 3.5: Global coordinate system with unit vectors i, j and k in the directions of axes x, y and z (adapted from Robertson et al., 2014). .......45
Figure 3.6: The origin of the pelvis (adapted Robertson et al., 2014). .......47
Figure 3.7: Reference frames attached to the body segments (pelvis, upper trunk, scapula, right upper arm, right forearm, right hand, left upper arm, left forearm and left hand) and ball when seen from the front of the subject ..............................................................................49
Figure 3.8: Raw (dotted line) and smoothed (solid line) translation of the midpelvis (left) and orientation angles of the upper trunk (right). ......51
Figure 3.9: Raw (dotted line) and smoothed (solid line) orientation angles of the scapula (left) and right upper arm (right). ......................52
Figure 3.10: Raw (dotted line) and smoothed (solid line) orientation angles of the right forearm (left) and right hand (right). ......................53
Figure 4.1: Segments used within the simulation model. ...................................................................................................................56
Figure 4.2: The simulation model representing the pitcher showing twenty orientation angles for each joint and three linear translations at midpelvis..................58

Figure 4.3: The pitcher grip a two-seam fastball (left). The contact and release phase (right).........................................................62

Figure 4.4: An example of ball release of Trial 5 with a close-up view; wrist (solid line) and ball horizontal displacement (dotted line). Ball release at time zero.................................................................63

Figure 4.5: The Cardan rotation sequence XYZ of rotations first about (a) the x-axis of the stationary coordinate system (α); then about (b) the y’-axis (β); and finally about (c) the z’’-axis (γ)........................................64

Figure 4.6: The resultant speed obtained from the simulation model (solid line) and experiment (dotted line). .........................................................69

Figure 4.7: Displacement (left) and linear velocity (right) of midpelvis of Trial 20: simulation model (solid line) and experiment (dotted line).......75

Figure 4.8: Displacement (left) and linear velocity (right) of right pelvis of Trial 20: simulation model (solid line) and experiment (dotted line).......76

Figure 4.9: Displacement (left) and linear velocity (right) of left pelvis of Trial 20: simulation model (solid line) and experiment (dotted line).......77

Figure 4.10: Displacement (left) and linear velocity (right) of suprasternal of Trial 20: simulation model (solid line) and experiment (dotted line)....78

Figure 4.11: Displacement (left) and linear velocity (right) of right shoulder of Trial 20: simulation model (solid line) and experiment (dotted line)....79

Figure 4.12: Displacement (left) and linear velocity (right) of right elbow of Trial 20: simulation model (solid line) and experiment (dotted line)....80

Figure 4.13: Displacement (left) and linear velocity (right) of right wrist of Trial 20: simulation model (solid line) and experiment (dotted line)....81

Figure 4.14: Displacement (left) and linear velocity (right) of the ball of Trial 20: simulation model (solid line) and experiment (dotted line)........82

Figure 5.1: A ramp up and ramp down torque generator activation profile. ...92

Figure 5.2: A ramp down and ramp up torque generator activation profile. ...93

Figure 5.3: An example of a surface fit to torque data for shoulder flexion (adapted from Jackson, 2010). .................................................................94

Figure 5.4: Hyperbolic functions to describe the eccentric and concentric phases. ..................................................................................97

Figure 5.5: The three parameter differential activation function..................98

Figure 5.6: An example of the seven parameter function fitted for the upper trunk extension torque.................................................................101

Figure 6.1: Joint angles time-histories for a matched simulation of Trial 20 (torque-driven: solid line, angle-driven: dashed line)......................110

Figure 6.2: Activation profiles for the individual angles of Trial 20.............111
Figure 6.3: Activation profiles for the individual angles of Trial 20............ 112
Figure 6.4: Joint torque time-histories for a matched simulation of Trial 20. .......................................................................................................... 113
Figure 6.5: A torque generator activation profile: ramp up, ramp up and ramp down. ................................................................. 118
Figure 6.6: A torque generator activation profile: ramp down, ramp down and ramp up......................................................... 118
Figure 7.1: Comparison of the joint angle time-histories for optimal technique (solid line) and matching simulation (dashed line) of Trial 20. .............................................................................................................. 125
Figure 7.2: Comparison of the joint activation level for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20. .............................................................................................................. 126
Figure 7.3: Comparison of the joint activation level for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20. .............................................................................................................. 127
Figure 7.4: Comparison of the joint torque time-histories for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20. .............................................................................................................. 128
Figure 7.5: Comparison of the joint angular velocity time-histories for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20. .............................................................................................................. 129
Figure 7.6: Comparison of the joint angle time-histories for optimal technique for actual strength (dashed line) and increased strength (solid line) of Trial 20................................................................. 133
Figure 7.7: Comparison of the torque generator activation level for actual strength (dashed line) and increased strength (solid line) of Trial 20..... 134
Figure 7.8: Comparison of the torque generator activation level for actual strength (dashed line) and increased strength (solid line) of Trial 20..... 135
Figure 7.9: Comparison of the joint torque time-histories for actual strength (dashed line) and increased strength (solid line) of Trial 20..... 136
Figure 7.10: Comparison of the joint angle time-histories for optimal technique for increased strength (dashed line) and varied increased strength (solid line) of Trial 20. ................................................................. 139
Figure 7.11: Comparison of the torque generator activation level for increased strength (dashed line) and varied increased strength (solid line) of Trial 20. .............................................................................................................. 140
Figure 7.12: Comparison of the torque generator activation level for increased strength (dashed line) and varied increased strength (solid line) of Trial 20................................................................................................. 141
Figure 7.13: Comparison of the joint torque time Histories for increased strength (dashed line) and varied increased strength (solid line) of Trial 20. ................................................................. 142

Figure A1: Orientation of pelvis about x-axis, y-axis and z-axis, respectively. ................................................................. 168

Figure A2: Orientation of upper trunk about x-axis, y-axis and z-axis, respectively. ................................................................. 169

Figure A3: Orientation of scapula about y-axis and z-axis, respectively. ........... 170

Figure A4: Orientation of right upper arm about x-axis, y-axis and z-axis, respectively. ................................................................. 171

Figure A5: Orientation of right forearm about x-axis, y-axis and z-axis, respectively. ................................................................. 172

Figure A6: Orientation of right forearm about x-axis and y-axis, respectively. ................................................................. 173

Figure A7: Orientation of left upper arm about x-axis, y-axis and z-axis, respectively. ................................................................. 174

Figure A8: Orientation of left forearm about x-axis. ......................... 175

Figure E1: The anatomical position, where the angle of each joint is defined as (0,0,0). ................................................................. 215

Figure E2: Angle ranges for the (A) trunk and pelvis, (B) upper arm, (C) forearm and (D) hand. ................................................................. 215

Figure E3: Movement in the sagittal plane (rotation about x-axis). .......... 216

Figure E4: Movement in the frontal plane (rotation about y-axis). ........... 217

Figure E5: Movement in the transverse plane (rotation about z-axis). ....... 218

Figure F1: Displacement (left) and linear velocity (right) of midpelvis of Trial 10: simulation model (solid line) and experiment (dotted line). 219

Figure F2: Displacement (left) and linear velocity (right) of right pelvis of Trial 10: simulation model (solid line) and experiment (dotted line). 220

Figure F3: Displacement (left) and linear velocity (right) of left pelvis of Trial 10: simulation model (solid line) and experiment (dotted line). 221

Figure F4: Displacement (left) and linear velocity (right) of suprasternal of Trial 10: simulation model (solid line) and experiment (dotted line). 222

Figure F5: Displacement (left) and linear velocity (right) of right shoulder of Trial 10: simulation model (solid line) and experiment (dotted line). 223

Figure F6: Displacement (left) and linear velocity (right) of right elbow of Trial 10: simulation model (solid line) and experiment (dotted line). 224

Figure F7: Displacement (left) and linear velocity (right) of right wrist of Trial 10: simulation model (solid line) and experiment (dotted line). 225

Figure F8: Displacement (left) and linear velocity (right) of the ball of Trial 10: simulation model (solid line) and experiment (dotted line). ......... 226
Figure F9: Displacement (left) and linear velocity (right) of mid-pelvis of Trial 13: simulation model (solid line) and experiment (dotted line)...... 227

Figure F10: Displacement (left) and linear velocity (right) of right pelvis of Trial 13: simulation model (solid line) and experiment (dotted line)...... 228

Figure F11: Displacement (left) and linear velocity (right) of left pelvis of Trial 13: simulation model (solid line) and experiment (dotted line)...... 229

Figure F12: Displacement (left) and linear velocity (right) of suprasternal of Trial 13: simulation model (solid line) and experiment (dotted line)...... 230

Figure F13: Displacement (left) and linear velocity (right) of right shoulder of Trial 13: simulation model (solid line) and experiment (dotted line)...... 231

Figure F14: Displacement (left) and linear velocity (right) of right elbow of Trial 13: simulation model (solid line) and experiment (dotted line)...... 232

Figure F15: Displacement (left) and linear velocity (right) of right wrist of Trial 13: simulation model (solid line) and experiment (dotted line)...... 233

Figure F16: Displacement (left) and linear velocity (right) of the ball of Trial 13: simulation model (solid line) and experiment (dotted line)...... 234
CHAPTER 1
INTRODUCTION

1.1 Introduction

This chapter provides a general overview of the area of overarm throwing in fastball pitching and its associated research. The statement of purpose is addressed and specific research questions to be answered later in the study are presented.

1.2 The Area of Study

Overarm throwing is an important basic skill in many sports such as in baseball, javelin, water polo, cricket etc. In baseball, the fastball pitcher uses an overarm throwing movement to project the ball with maximum speed so that the batter fails to hit the ball. This study focuses on overarm throwing, particularly fastball pitching with the aim to understand what factors affect ball release speed.

The game of baseball is played between two teams, each consisting of nine players; a pitcher, a catcher, first baseman, second baseman, shortstop, third baseman, left fielder, centre fielder and right fielder. A game of baseball consists of nine innings. One innings is divided into two halves; in the top half of the inning, one team will play in the field and the second team comes to bat, and in the bottom half, the teams reverse roles. The team that is batting during a particular half-inning is trying to score runs. The team with the higher number of runs at the end of the nine innings is the winner of the game.
During an inning, a player on the team in the field, called a pitcher, throws a baseball toward a player of the team at bat, called the batter. The batter will try to hit the ball in a location out of the reach of the players in the field. By hitting the ball, the batter has the opportunity to run around four bases that lie in the field. If a player advances around all of the bases, he has scored a run. If a batter hits a ball that can be caught, or that can be thrown to first base before he runs to that base, then he is said to be out, and cannot score a run. A batter is also out if he fails to hit the baseball three times or if three good pitches have been thrown and caught by the catcher. The objective for the batting team during an inning is to score as many runs as possible before obtaining three outs. The objective of the pitcher is to pitch so that the batter fails to hit the baseball.

Baseball pitching can be divided into six phases; wind-up, lead foot contact, preparation phase (arm cocking), arm acceleration, arm deceleration and follow through (Fleisig and Escamilla, 1996). The objectives of fastball pitching are to achieve a high ball release speed and accuracy at the target (Atwater, 1979; Calabrese, 2013). The average ball speed reported in previous studies is between 21.0 m/s and 39.0 m/s (Atwater, 1979; Campbell et al., 2010; Escamilla et al., 2002; Elliot et al., 1988; Feltner and Dapena, 1986; Tarbell, 1971; Werner, 2008) with a standard ball of mass 0.145 kg and circumference of 23.0 cm.

1.3 Problem Statement

The pitching motion is a complex sequence of movements involving the transfer of momentum from the lower extremity to the upper extremity and finally to the ball. The time between front foot contact and ball release is about 0.145 seconds (Stodden et al., 2008) followed by an additional half second for the ball to reach the home plate (Escamilla et al., 1998). The shoulder and elbow are exposed to high risk of injuries due to this rapid and repetitive motion. Additionally, alterations in pitching kinematics will alter the pitching kinetics, which can increase injury risk especially on the shoulder and elbow (Feltner and Dapena, 1986). Studies have also suggested that pitching types, pitching counts, and pitching mechanics have an influence on
this issue (Fleisig et al., 1995; Lyman et al., 2002). The focus of this study will be on the pitching mechanics to help make improvements in fastball pitching performance rather than to help to reduce the risk of injury.

Most of the previous studies have focused on the kinematics (Escamilla et al., 2007; Feltner and Dapena, 1986; Fleisig et al., 1995) and kinetics including joint force and moment (Fleisig and Escamilla, 1996; Fleisig et al., 2006; Feltner and Dapena, 1986) analysis in the upper extremities. Until recently, only foot-ground reaction forces have been studied for the lower extremity (Kageyama et al., 2014; MacWilliams et al., 1998). An electromyography (EMG) system has also been applied in baseball pitching studies and used to study the muscle activation in baseball pitching (Glousman et al., 1988; Watkins et al., 1989). Computer simulation models have been developed to investigate further the mechanics of overarm throwing (Chowdhary and Challis, 2001; Felter and Dapena, 1986; Felter and Dapena, 1989; Fujii and Hubbard, 2002; Hong et al., 2001). Contributions of body segments to ball speed were investigated by restricting the motion of body segments involved in the throwing motion (Roach and Lieberman, 2014).

The pitcher and coach aim to use training regimes and technical strategies to maximise performance. However, using a pitcher to investigate different throwing techniques experimentally could lead to injury. Alternatively, computer simulation models are able to replicate the movement whilst safely investigating technical strategies to enhance performance (Feltner and Dapena, 1986; Hong et al., 2001; Fuji and Hubbard, 2002; Hirashima et al., 2008; Naito and Maruyama, 2008; Naito et al., 2014).
1.4 Statement of Purpose

It is the intention of the present study to understand the mechanics of overarm throwing, particularly in fastball pitching. The aims of this study are summarised below:

(i) To gain an understanding of the mechanics of overarm throwing, specifically in fastball pitching.
(ii) To identify what elements are needed in a computer simulation model of overarm throwing in order to provide an accurate representation of fastball pitching.
(iii) To apply such a model to the maximisation of overarm throwing speed.

1.5 Research Questions

This research project will focus on the following questions:

1. What complexity of torque-driven simulation model is required to accurately simulate overarm throwing?

It is not clear what level of complexity is essential to accurately simulate overarm throwing. The focus of this research study will be on the torso and upper body and so although the effect of the lower limbs will be accounted for, it is not the aim of this study to model the legs directly. The linear and angular speed of the midpelvis which represents the lower limb will be analysed to determine the contribution of lower limb movement to ball release speed. Kinematic data obtained from fifteen trials and an angle-driven model will be used to investigate the complexity required to accurately represent overarm throwing.
2. How close to optimal is the technique of the fastball pitcher in this study?

A computer simulation model will be used to investigate the technique of a fastball pitcher. Subject-specific mass, inertia, anthropometry will be obtained from the fastball pitcher whilst three-dimensional kinematic data will provide a detailed representation of the technique used. Subject-specific optimal performance will be determined by optimising the torque generator activation time histories which govern the movement of the model to maximise ball release speed.

3. How does a 5% increase in strength affect ball release speed?

An understanding of the kinematics and kinetics of pitching can assist in technique and strength-training programs that focus on performance enhancement and injury prevention. Trunk strength is a very important consideration when training for a complex ballistic movement that demands effective transfer of momentum through the kinetic chain (Stodden et al., 2005; Solomito et al., 2015). Utilising stronger trunk flexion and trunk rotation helps in the efficient transfer of momentum which increases ball release speed. Ball release speed achieved indicates that strength, anthropometric measures, and technique might be related to ball speed (Atwater, 1979). A computer simulation model of overarm throwing will be used to investigate the effects of a 5% increase in strength on ball release speed.

4. How does a ±30% change in strength affect ball release speed?

Permitting the strength at all joints to be varied by ±30% will allow more understanding on which joint benefits more from an increase in strength. Additionally, it can also be observed whether more than a 5% strength increase in a particular joint is required to achieve a higher ball release speed. To answer the research question, the strength at all joints will be varied by ±30% and ball speed maximised through changing the seven activation parameters per torque generator.
1.6 Chapter Organisation

Chapter 2 reviews the literature on overarm throwing: specifically the fastball pitching, throwing characteristics, simulation models and techniques of investigation. The pros and cons of different research techniques are discussed and limitations of previous research identified.

Chapter 3 describes the collection of kinematic data which will be used in the angle-driven and torque-driven models.

Chapter 4 presents the development of the angle-driven model of overarm throwing.

Chapter 5 describes how the model parameters are determined for input to the angle-driven and torque-driven models.

Chapter 6 outlines the procedure for the evaluation of the torque-driven model. This includes using an objective score to compare simulation outputs with performances.

Chapter 7 applies the model to maximise ball release speed. In addition, answers to the specific research questions addressed in Chapter 1 are discussed using results from the optimisations.

Chapter 8 summarises the main findings of the study regarding optimal throwing techniques for maximum ball release speed and discusses the limitations of the present study with suggestions for future research.
CHAPTER 2
LITERATURE REVIEW

2.1 Chapter Overview

The review of literature is divided into three sections. The first section describes throwing in general including explanations of fastball pitching grips and phases of pitching. The second section of the review is on experimental studies of baseball pitching. The contributions of each segment and pitching mechanics are described in this section. Finally a review of theoretical studies on overarm throws in baseball pitching focused on the fastball is described. For completeness research on aspects such as injury are included in the review of literature although these are not the focus of the present thesis.

2.2 Throwing Background

During the past few decades, pitching research has tended to change from qualitative studies to quantitative studies. Biomechanical studies of elite performances have provided useful information and have given a better understanding of pitching techniques (Escamilla et al., 2007; Feltner and Dapena, 1986; Fleisig et al., 1995; Lin et al., 2003; Ramsey et al., 2014; Ramsey and Crotin, 2015; Wang et al., 1995). Computer simulation models have been developed to further investigate the mechanics of baseball pitching (Feltner and Dapena, 1986; 1989; Fujii and Hubbard, 2002; Hong et al., 2001; Naito et al., 2014). Sabermetrics, the mathematical and statistical analysis of baseball records, measures the effectiveness of batters and pitchers and has been set up to provide a reference for coaches and baseball players.
There are several types of throwing motion such as overarm throwing, underarm throwing and sidearm throwing. The focus of this thesis is on overarm throwing. Therefore, the review will cover overarm throwing, specifically fastball pitching although some reference to other types of throwing motions will be included. This section will start with some explanations on pitching grips which are important to determine the ball orientation and pitching type. The explanations will help to determine which pitching grips will be used in this study. The section is followed by some explanations on different phases in fastball pitching.

### 2.2.1 Pitching Grips

During pitching, the ability of the pitchers to manipulate several techniques of throwing such as fastball, curveball, change-up and slider is beneficial to ‘confuse’ and reduce the time for the batter to alter the bat velocity and trajectory. The main difference characteristics among these techniques are the ball axis of rotation or seam orientation and the direction of the spin which will cause different flight patterns (Alaways and Hubbard, 2001; Bahill and Baldwin, 2007; Jinji and Sakurai, 2006; Sakurai et al., 1993).

The elbow, wrist and hand position, and different grip types will affect the relative position of the fingers and ball. This produces different pitching techniques and changes the ball speed (Bahill and Baldwin, 2007; Wang et al., 2013). By manipulating different types of grip and by changing the angle of the wrist and elbow, the pitcher is able to get a batter out and prevent the ball from being hit.

Commonly used pitching grips in fastball are the four-seam fastball (subsection 2.2.1.1) and the two-seam fastball (subsection 2.2.1.2).
2.2.1.1 Four-seam Fastball

Figure 2.1: Four-seam fastball grip (adapted from www.thecompletepitcher.com).

Figure 2.1 shows the four-seam fastball grip or also known as a straight pitch. It is the most common pitch used by the pitcher to get ahead in the count or when the pitcher needs to throw a strike. This type of fastball has minimal lateral movement. The fastball four-seam spin direction produces backspin, which creates high pressure under the ball and low pressure on top resulting in the illusion of the ball rising (Figure 2.3). For data collection, the markers can be set as in Figure 2.2.

Figure 2.2: Marker location (adapted from Alaways and Hubbard, 2001). The ball on the left is in the two-seam configuration and the ball on the right is in the four-seam configuration.
2.2.1.2 Two-seam Fastball

Figure 2.4: Two-seam fastball grip (adapted from www.thecompletepitcher.com).

Figure 2.3: Four-seam and two-seam spin direction (adapted from Kensrud et al., 2015).

Figure 2.4 shows the two-seam fastball grip or also known as the movement pitch. The spin direction produces sidespin that causes the ball to cut in as it approaches the batter (Figure 2.3). The speed of the two-seam fastball is normally slower by 1 to 3 mph (0.45 m/s to 1.34 m/s) compared to the four-seam fastball. Pitchers normally start throwing using the two-seam fastball. With the combination of control, high velocity and breaking ball (the ball does not travel straight as it approaches the batter), the two-seam fastball can be one of the most effective pitches in baseball (Mattingly and Rosenthal, 2007). In this study, the pitcher will use the two-seam fastball grip. The markers on the baseball will be located on the large area as shown in Figure 2.2.
2.2.2 Phases of Pitching

The pitching movement consists of six phases: wind-up, early cocking/stride, late cocking, acceleration, deceleration and follow-through (Calabrese, 2013; Dillman et al., 1993; Escamilla et al., 2007; Fleisig and Escamilla, 1996; Kageyama et al., 2014; Seroyer et al., 2010; Stodden et al., 2001). The time between front foot contact and ball release is about 0.145 seconds (Stodden et al., 2008) followed by an additional half second for the ball to reach home plate (Escamilla et al., 1998). As ball velocities increased, time from stride foot contact to ball release decreased significantly and represented 39.7% of the change in ball velocity (Stodden et al., 2006).
2.2.1 Wind-up

The wind-up begins with the pitcher’s move from the static position. From a standing position facing the batter (Figure 2.5a), the pitcher initiates the throw by stepping backward with what will become the stride leg (Figure 2.5b). With the bodyweight momentarily supported by the stride leg, the supporting (pivot/back) leg is turned laterally (Figure 2.5c) to allow maximum generation and transfer of
momentum and force to the upper extremity and ball (Dillman et al., 1993; Seroyer et al., 2010; Werner et al., 2008). When the weight is shifted from the stride leg to the supporting (pivot/back) leg, the windup is initiated (Figure 2.5d). As the windup is initiated, the body rotates 90°, and the striding leg is elevated and flexed so that the left side of the body is now facing the batter (Figure 2.5e). The windup phase is completed with elevation of the lead (stride) leg to its highest point and with separation of the throwing hand/ball from the glove (Figure 2.5f). Concentric contraction of the hip flexors promotes hip flexion of the lead (stride) leg, whereas the hip extensors, knee extensors, and knee flexors dynamically stabilise the back leg and hip musculature to promote a quasi-static (almost static) balance point (Campbell et al., 2010). Six kinematic parameters which are important during the wind-up phase are the stride length, elbow flexion, shoulder external rotation, shoulder abduction, shoulder extension and knee flexion (Escamilla et al., 2007; Dillman et al., 1993).

2.2.2.2 Early Cocking/Stride

After the wind-up, the back leg is flexed, thus lowering the body, and the lead leg is moved towards the catcher. The stride phase begins once the lead leg reaches its maximum height and the hand with ball is removed from the glove (Figure 2.5g). This phase ends when the lead foot contacts the ground (Figure 2.5k). The position of the stride leg and the stride length are two important criteria in this phase which functions to produce linear trunk velocities and is the initial factor in the momentum generation for transfer to the upper extremity through the kinetic chain during throwing (Stodden et al., 2006). The stride leg should land almost directly in front of the back leg, with toes pointing slightly in (Figure 2.6). If the stride leg is placed too much toward the pitcher’s right, the pitcher may end up throwing across his body, which means that the hips will not be able to rotate and the athlete will end up throwing without much energy contributed by the lower body. Conversely, if the foot is placed too much to the left, the pitcher is too open which will cause the hips to rotate and face the batter too early. As a result of such improper timing, energy from the hips will be applied to the trunk too soon and will not help the upper trunk to rotate. The stride length should be long enough for the pitcher to stretch out the
body but not so long that the athlete cannot rotate his legs and hips properly (Dillman et al., 1993). In addition, lengthening the stride by keeping the head behind the hips longer is able to reduce shoulder distraction in baseball pitchers (Werner et al., 2007). Escamilla et al. (1998) found that highly skilled and proficient baseball pitchers throw with stride lengths that range between 80% and 85% of body height. In addition, the lag effect of the upper trunk facilitated by the trunk’s linear movement in the sagittal plane (via the stepping action) and the high rotational trunk velocities promote trunk extension just after stride foot contact (Stodden et al., 2006). The position of the upperarm and forearm at stride foot contact are critical too, as they place the upper extremity in a position to optimise transfer of momentum from the lower extremities and trunk to the distal segment and the ball (Stodden et al., 2005). As the lead foot contacts the ground, the arm cocking phase begins.
2.2.2.3 Late Cocking

The late cocking phase occurs between lead foot contact and the point of maximum upper arm external rotation (Figure 2.5I-o). During this phase, the pelvis reaches its maximum rotation, the upper trunk undergoes twisting, extension and lateral tilt, the scapula is brought into a position of retraction, the forearm flexes and the upper arm undergoes abduction and external rotation. The knee of lead leg begins to extend, forming a solid base for trunk flexion (Seroyer et al. 2010). As the trunk rotates and faces the batter, the upper arm achieves maximum external rotation, and the arm cocking phase is completed (Dillman et al., 1993). An increase in pelvis and trunk
orientations and velocities at the instant of maximum upper arm external rotation is able to increase the ball velocity because more angular momentum is allowed to be transferred to the upper extremity (Stodden et al., 2001; 2006). Shorter time intervals from lead foot contact to maximum upper arm external rotation also correspond to greater ball speed (Werner et al., 2008). Additionally, the improper coordination of the trunk, upper arm and forearm movement during this phase might cause the shoulder to generate high force in order to maintain the velocity (Seroyer et al., 2010). Five significant kinematic parameters during the arm cocking phase are: maximum pelvis angular velocity, maximum upper trunk angular velocity, maximum forearm flexion, maximum upper arm external rotation and maximum upper arm extension (Escamilla et al., 2007).

2.2.2.4 Acceleration

The acceleration phase is defined as the time between maximum upper arm external rotation to the instant of ball release (Figure 2.5p-u). Rapid movement can be observed in this phase because it takes about 42-58 ms of the total pitch timing sequence (Dillman et al., 1993). High levels of muscle activity from hip flexor and abdominal musculature have been demonstrated during the acceleration phase and promote trunk and hip flexion (Fleisig and Escamilla, 1996). In this phase, the trunk continues to rotate and tilt, initiating the transfer-of-angular momentum through the upper extremity. The scapula protracts to maintain a stable base as the upper arm undergoes rapid internal rotation (Seroyer et al., 2010; Escamilla et al., 2007). To accelerate the arm to a greater angular velocity, the pitcher extends the forearm which will reduce the moment-of-inertia of the mass that must be rotated about the longitudinal axis of the upper arm (Dillman et al., 1993). The trunk is flexed, the forearm is almost in a fully extended position, and the upper arm is undergoing internal rotation when the ball is released. In the acceleration phase, three significant kinematic parameters are: maximum forearm extension angular velocity, maximum upper arm internal rotation angular velocity and upper arm abduction (Escamilla et al., 2007).
2.2.2.5 Deceleration

After ball release, the forearm continues to extend and the upper arm internally rotates (Dillman et al., 1993; Seroyer et al., 2010). The deceleration phase occurs between ball release and maximum upper arm internal rotation and forearm extension (Figure 2.5v). Six kinematic parameters which are important at the instant of ball release are knee extension of the lead leg, forward trunk tilt, lateral trunk tilt, upper arm extension, forearm flexion and ball velocity (Escamilla et al., 2007).

2.2.2.6 Follow-through

Follow-through is completed with extension of the stride leg, hip in flexion position, upper arm adducted, forearm flexed and in supination position (Seroyer et al., 2010; Escamilla et al., 2007) (Figure 2.5v-w).

2.3 Previous Experimental and Theoretical Studies

2.3.1 Contribution of Segment rotations to Ball Velocity

Efficient throwing mechanics is predicated on a pitcher’s ability to perform a sequence of movements in the body segments, which progresses from the legs, pelvis, and trunk to the smaller, distal arm segments.

The momentum generated by the larger segments is transferred to the adjacent distal segments by appropriately timing the movement of the pelvis and trunk in a manner that ideally follows the summation of speed principle which demonstrates a proximal-to-distal sequential pattern (Putnam, 1993). The summation of speed principle stated that to maximize the speed at the distal end of a linked system, the movement should start with the more proximal segments and progress to the more distal segments such that each segment starts its motion at the instant of greatest speed of the preceding segment and reaches a maximum speed greater than that of its predecessor (Bunn, 1972). The principle suggests that the speed of the distal end of the linked system is built up by summing the individual speeds of all segments.
participating in the sequence. Errors in timing and coordination among body segments will result in decreasing ball velocity (Fleisig et al., 2009; Stodden et al., 2005; Urbin et al., 2012) which will result from a decrease in the angular momentum transferred from the larger segments to the throwing arm. Therefore, each segment plays a vital role to achieve maximum ball velocity at ball release. In this subtopic, the contribution of the body segments to ball velocity are reviewed which will help in the construction of a computer simulation model of overarm throwing.

2.3.1.1 Lower Extremity

The lower extremity provides a stable centre-of-mass to allow maximum generation and transfer-of-momentum during an overarm throw via the kinetic chain, through the pelvis, trunk, upper arm, forearm, and eventually the hand before ball release (Dillman et al., 1993; Escamilla et al., 1998; Stodden et al., 2006). The lower extremity and trunk provide the beginning of the kinetic chain that ends with force transmission to the baseball at the time of ball release.

Previous studies show that the role of the lower extremity is no more than to stabilise the trunk and upper extremity (Kibler, 1991). As example, a study by Elliot et al. (1988) shows that the pitchers drive their upper body forward as the lead foot is completely on the ground. The trunk rotation in the transverse plane and the forward movement of the throwing limb occurs only after the lead foot is stabilised on the ground. MacWilliams et al. (1998) examined the relationship between forces generated by the lower extremities and the linear wrist velocity. Their study found that forces generated in the plane of the pitch were related to the linear wrist velocity when the pitchers were examined as a group. However when examined by the individual, the correlations between forces and wrist velocity were varied. Some pitchers exhibited trends similar to the group, with wrist velocity increasing with increasing forces. Others demonstrated an opposite trend, with higher forces correlating with diminished wrist velocities. This difference suggests that there may be an effect of attempting to overthrow, with loss of velocity resulting from attempts to generate unnaturally high push-off forces from the lower extremities. In an evaluation on the lower extremity muscles, Yamanouchi (1998) found that the hip
adductor was the main source of momentum generation for transfer to the upper extremities and helped to stabilise the trunk and the upper part of the body during the deceleration in the latter phase of pitching. The study by Yamanouchi (1998) was extended by Campbell (2010) who found very high activation levels of the gastrocnemius (GAST), vastus medialis (VM), rectus femoris (RF) and gluteus maximus (GM) in the stride (lead) and back legs during stride foot contact to ball release which explains the important roles of these muscles to stabilise the knee joint when the upper extremity and trunk forcefully rotate about the stride (lead) hip. From ball release to 0.5 seconds after ball release, this muscle activity (GAST, VM, RF and GM) produced by the stride (lead) leg helps to stabilise the hip and knee joints to maintain a standing posture and helps a controlled follow-through.

The extended stride (lead) knee helps brace and stabilise the lead leg which enhances the ability of the trunk to more effectively flex forward over the lead leg. Although strength and the position of lead leg (leg on the opposite side of the throwing arm) at foot plant is critical to optimising performance during the throwing motion, baseball pitchers have significantly smaller amounts of hip internal rotation range-of-motion and abduction strength of the back leg compared with position players (Laudner et al., 2010). The largest excursions of joint motion in the lower extremity occurred at the hip joint in the coronal and sagittal planes in both the stride (lead) and back legs (Milewski et al., 2012). This is due to the circumstance that pitchers rely more on energy created in the core and upper extremity compared to the position players whom rely more energy on the lower extremity (Laudner et al., 2010).

Peak hip flexion/extension and adduction velocities and knee flexion and extension velocities were much lower than those found in the upper extremity (Nissen et al., 2007). Peak knee extension velocity of the lead leg is much lower in amplitude and occurs just before ball release and therefore has less of a role in transferring energy (Milewski et al., 2012).

In view of previous studies on the role of lower extremity on pitching performance and also for simplicity, it was decided to exclude a direct representation of the lower
limbs from the angle-driven (Chapter 4) and torque-driven model (Chapter 5). As an alternative the movement of the lower limbs was included by constraining the pelvis to translate in the same way as the recorded performances. This approach has been successfully used in other simulation models of upper limb tasks (for example one-handed backhand strokes in tennis where only the trunk, arm and racket were modelled (Kentel et al., 2011; King et al., 2011).

2.3.1.2 Pelvis, Trunk and Shoulder Complex

Research has shown that good hip range of motion and strength in throwing athletes will result in greater performance and decreased stress placed on the upper extremity (Laudner et al., 2010; Stodden et al., 2005; Urbin et al., 2012). Proper alignment of the pelvis (Figure 2.6) with the intended target at lead foot contact, at maximal upper arm external rotation, and at ball release have been shown to decrease maximal forces and torques on the arm and increase ball velocity (Stodden et al., 2001; Wight et al., 2004). Trunk rotation during arm cocking and trunk forward tilt at ball release as well as increasing trunk strength are crucial to generate angular velocity within the trunk for maximum ball velocity (Feltner and Nelson, 1996; Stodden et al., 2001; 2006). Proper timing between the pelvis and upper trunk rotations is thought to be critical in the transfer-of-momentum from large base segments (i.e. legs and trunk) to the arm segments (Aguinaldo et al., 2007; Sachlikidis and Salter, 2007).

Studies were done to investigate the contributions of trunk and hip rotation to ball velocity (Hong and Robert, 1993; Naito et al., 2011; Robb et al., 2010; Stodden et al., 2001; Wight et al., 2004). The pitching movements were divided into six events, i.e. the instant of stride foot contact, the instant of beginning ball deceleration, the instant of ball acceleration, the time of initiation of forearm extension, the time of initiation of upper arm internal rotation and the instant of ball release. The lateral tilt of the upper trunk contributed to the ball speed mainly during a short period from the beginning of ball deceleration to the start of forearm extension. After the instant of stride foot contact, the hip external/internal rotation was the major contributor to ball velocity during the period from the beginning of ball deceleration to the start of ball acceleration. The forward tilt of the upper trunk and hips contributed to the ball
speed from the beginning of ball acceleration to the time of ball release (Fleisig et al., 2009). The trunk twist contributed to ball speed considerably during the period from the start of ball acceleration to the start of upper arm internal rotation. In addition, the contribution of upper arm velocity to ball velocity was about 40% at the time of stride foot contact, 60% near the time of ball deceleration, 35% at the time of ball acceleration, 12% at the time of forearm extension, 10% at the time of upper arm internal rotation, and 8% at the time of ball release.

The influence of trunk movement on shoulder and elbow joint kinematics in pitching has been documented (Feltner and Dapena, 1986; 1989). Trunk rotation contributes to forearm extension at the elbow. Trunk rotation decelerates as forearm extension begins, presumably to facilitate the transfer-of-angular momentum from the trunk to the forearm (Atwater, 1979). The forces resulting from rapid trunk rotation about its longitudinal axis and upper arm flexion torque are primarily responsible for producing upper arm external rotation and forearm abduction after stride foot contact (Feltner and Dapena, 1986; 1989; Oyama et al., 2014). Achieving peak pelvis rotation velocity before peak upper trunk rotation velocity will lead to efficient pitching performance, whereas reversal in the order of peak rotation velocities will result in decreased ball velocity and/or compensation in the upper extremity joint movements, which may lead to increase joint loading and injury at the shoulder (Aguinaldo et al., 2007; Laudner et al., 2010; Oyama et al., 2013; 2014). Aguinaldo et al. (2007) investigated how the motion of the trunk could affect the shoulder joint torque of baseball players of various skill levels. The results showed that those pitchers who initiated trunk rotation later in the pitching cycle had lower internal rotation shoulder torque (Aguinaldo et al., 2007; Oyama et al., 2014). Oyama et al. (2013) investigated the effects of excessive contralateral trunk tilt on 72 high school baseball pitchers. Excessive contralateral trunk tilt was observed at the instant of maximal shoulder external rotation by examining whether the side of the pitcher’s head ipsilateral to the throwing limb deviated by more than a head width from a vertical line passing through the pitcher’s stride foot ankle. Compared with pitchers who did not demonstrate excessive contralateral trunk tilt, those with excessive contralateral trunk tilt pitched at a higher ball speed and experienced a greater proximal force at the proximal end of the elbow, greater proximal force at
the proximal end of the shoulder, elbow adduction torque and shoulder internal rotation torque (Oyama et al., 2013; 2014). Pitchers with excessive contralateral trunk tilt demonstrated less upper trunk flexion at stride foot contact, less upper trunk twist, and greater upper trunk extension at maximum upper arm external rotation and at ball release. An increase of 10° in contralateral trunk tilt will result in a 1.5% increase in ball velocity, a 3.2% increase in shoulder internal rotation torque and a 4.8% increase in elbow adduction torque (Oyama et al., 2013; Solomito et al., 2015). Although an increase in contralateral trunk tilt will increase ball velocity, the increment is small compared to the increase of shoulder internal torque and elbow adduction torque. Pitchers will be exposed to the risk of injury especially at the shoulder and elbow if the excessive contralateral trunk tilt is incorporated into baseball pitching.

2.3.1.3 Throwing Arm

As the final two joints in the kinetic chain, the shoulder and elbow are vital elements in an overarm throw. The orientation of the upper extremity at stride foot contact and the segmental interactions between upper arm and forearm during the arm cocking and acceleration phases are critical to optimise transfer-of-momentum to the ball at release (Stodden et al., 2006).

Toyoshima et al. (1974) concluded that the maximum forearm extension angular velocity and ball velocity during fastball was due to the forearm being swung open like a whip by the rotary actions of other parts of the body, such as the pelvis, upper trunk, and upper arm; rather than by the forearm extending capabilities of the triceps. A whip-like effect is defined as the velocity of the proximal segment is decreased to allow the distal segments (i.e., the forearm and hand) to whip through and make a contribution to the action (Neal et al., 1991).

An induced acceleration analyses of the interaction torques show that the forearm extension during throwing is driven primarily by velocity-dependent forces generated by trunk rotation and upper arm internal rotation (Hirashima et al., 2008). In addition the hand flexion at the wrist during throwing is mostly driven by
velocity-dependent forces generated by forearm extension. The studies strongly suggests that power generated at more proximal joints (such as the pelvis, trunk and upper arm) is transferred to the throwing arm, producing a rapid, ‘whip-like’ accelerations of the arm and hand (Alexander, 1991; Atwater, 1979; Feltner, 1989; Hirashima et al., 2008; Putnam, 1993).

Feltner and Dapena (1986) found that the external rotation of the upper arm is produced by the inertial lag of the forearm and hand as the more proximal segments rotate forward. On the other hand, the extreme external rotation of the upper arm was due mainly to the sequential actions of the flexion and abduction muscles at the shoulder (Feltner, 1989). The subsequent stopping of the external rotation and production of internal rotation of the upper arm were due mainly to the actions of the internal rotation proximal joint torque at the shoulder (Feltner, 1989).

The acceleration of the forearm in the direction of elbow extension is caused primarily by the interactive moments resulting from the linear acceleration of the shoulder and the angular velocity of the upper arm (Feltner and Dapena, 1986; Feltner and Taylor, 1997). As the trunk is rotated counter-clockwise and the upper arm undergoes its abduction and extension rotations relative to the trunk, forces applied to the forearm at the elbow and directed along the longitudinal axis of the upper arm is essential to maintain the centripetal acceleration of the elbow relative to the shoulder (Feltner, 1989; Feltner and Dapena, 1986; Feltner and Taylor, 1997; Kim et al., 2009). Their finding suggests that the actions of the counter-clockwise rotation of the trunk produced forearm extension. Mechanically, when a force acting on the trunk, a force with equal magnitude but in the opposite direction will act on the upper arm. These forces will propagate to the elbow joint, forearm, and further upward to produce the angular movements of the adjacent segments.

Putnam (1993) stated that while the elbow extensors are active, the joint moment created is not large enough to explain forearm extension. The small magnitude of the extension torque at the elbow joint suggests that the acceleration of the ball may ultimately be due primarily to the actions of muscles other than the elbow extensors (Feltner and Dapena, 1986). This statement is in agreement with findings by Atwater
(1979) which shows effective throws can be accomplished with a radial nerve block preventing triceps action. Therefore, the extension of the forearm is not due primarily to the action of the triceps but due to the resultant joint force exerted by the upper arm on the forearm at the elbow.

In a study done by Feltner and Nelson (1996), the counter-clockwise rotation of the trunk, the flexion and external rotation of the upper arm at release allowed the forearm extension angular velocity to contribute approximately 4.4 m/s to the ball velocity at release. They emphasised that the forearm orientation appears to be more closely related to controlling the moment-of-inertia of the arm relative to the shoulder and not to positioning the hand and ball at release (Feltner and Nelson, 1996).

The wrist joint is not adequate to generate large flexion velocities which contribute to the ball speed (Hirashima et al., 2003) because the hand is mainly extended in either the arm-cocking or acceleration phase and slightly flexed by about $3 \pm 11^\circ$ at release (Barrentine et al., 1998). The strategy used by the central nervous system (CNS) is that the elbow and shoulder contributes to the adjustments of ball speed but the wrist does not (Feltner and Nelson, 1996; Hore et al., 2005; Jegede et al., 2005). As the length of the hand is shorter than that of the forearm and upper arm, the angular velocity of the wrist is less effective for increasing ball speed than the angular velocity of the elbow and shoulder which is one of the reasons why the wrist does not contribute to the adjustment of ball speed (Feltner and Nelson, 1996). In addition, the role of the wrist in fastball pitching is to simplify the control of the finger grip force for an accurate ball release.

Hore et al. (1996) investigated the contribution of finger flexion to ball speed in pitching. It was found that finger flexion occurred only after the ball is off the finger which presumably results from a reactive force associated with ball release. This finding indicated that finger flexion does not contribute to the generation of ball speed at release.
Regarding the positioning of the ball relative to the hand, Feltner and Nelson (1996) found that if the ball was rigid within the hand but located at a distance further from the wrist than the knuckle, any angular velocity of the hand would produce a larger speed for the ball than the knuckle. Therefore in the simulation model of overarm throwing, the ball will be positioned at the end of the hand by assuming that the ball slips to the distal end of hand at ball release.

### 2.3.1.4 Non-throwing Arm

The non-throwing arm acts as a pivot for the trunk or throwing arm to rotate about and was in an almost steady position while the throwing arm moved in a nearly circular path (Feltner, 1989; Murata, 2001). To observe the contribution of the non-throwing arm, Ishida and Hirano (2004) fixed the non-throwing arm to the trunk using a rubber band. The results were compared with the one obtained under normal conditions when the subject throws the ball without any arm restriction. It was observed that fixing the non-throwing arm to the trunk will increase the upper trunk twist 0.13 s prior to ball release resulting larger upper arm external rotation at stride foot contact and larger forearm flexion at ball release. In the restricted condition, the velocity of the ball at release dropped by about 10%. This result suggests that the contribution of the non-throwing arm to ball velocity was about 10%.

### 2.3.2 Pitching Mechanics

Most of the previous investigations have provided some knowledge about the pitching mechanics comprising the kinematic and kinetic parameters, the timing window and the pattern of proximal-to-distal sequencing which are able to contribute to increasing the ball velocity. In pitching, the critical factor to determine success in baseball is the ability of the pitcher to throw a ball with maximum velocity. Kinematic parameters such as knee extension of the lead leg, forward trunk tilt, extension of the forearm at elbow, external rotation of the upper arm at shoulder, and pelvis angular velocity have all been correlated with increased pitching velocity (Matsuo et al., 2001; Stodden et al., 2005; Werner et al., 2008).
2.3.2.1 Comparative Studies

Several comparative studies have been reported to promote further understanding of the mechanics of baseball pitching. Matsuo et al. (2001) compared twelve kinematic parameters between two groups of pitchers (high ball velocity group vs low ball velocity group). The intention was to observe the difference in kinematics between the two groups of pitchers. The twelve kinematic parameters were: the stride length which was measured in terms of body height percentage, pelvis linear velocity, pelvis rotation angular velocity, upper arm flexion angular velocity, knee flexion angular velocity of the lead leg, upper trunk rotation angular velocity, upper arm external rotation, forward trunk tilt angular velocity, forearm extension angular velocity, upper arm internal rotation angular velocity, knee extension angular velocity of the lead leg at the instant of ball release and forward trunk tilt at the instant of ball release. No significant differences were found in upper arm or forearm angular velocities between the groups. At the instant of ball release, the high velocity group demonstrated significantly less knee flexion angular velocity and significantly greater knee extension angular velocity of the lead leg compared to the low velocity group. Greater external rotation of the upper arm and forward upper trunk tilt were also observed in the high velocity group at the instant of ball release. In addition, comparing the timing parameters between these two groups demonstrated how a difference in segment sequential motion affects ball velocity. It was observed that the upper arm internal rotation angular velocity in low velocity group occurred after the instant of ball release which was slightly later compared to the high velocity group. The forearm extension angular velocity prior to the instant of ball release in the low velocity group also occurred slightly later compared to the high velocity group. Additionally, body height, arm length (upper arm plus forearm) and ball velocity were significantly greater in the high velocity group compared to the low velocity group; this explained a 15% difference in the ball velocity. Matsuo et al. (2001) found that segment length affects ball velocity. However, the study gave no detailed explanations regarding how changes in kinematic parameters influence the kinetic parameters.
To understand how different cultures and populations affect pitching mechanics, Escamilla et al. (2002) compared kinematic, timing and kinetic characteristics between American and Korean pitchers. At lead foot contact, the American pitchers had significantly greater upper arm flexion, while Korean pitchers exhibited significantly greater upper arm abduction and upper arm external rotation. During arm cocking, the American pitchers displayed significantly greater upper arm external rotation and greater pelvis angular velocity. The upper arm of the American pitchers moved through a greater range-of-motion during the arm acceleration phase which allowed the ball to travel more and helped to increase the ball velocity. At the instant of ball release, the American pitchers had 10° greater forward trunk tilt and 15° less knee flexion of the lead leg which contributed to higher ball velocity. There were no significant differences in timing measurement between American and Korean pitchers. During the arm-cocking phase, the American pitchers exhibited 29% greater shoulder internal rotation torque and 33% greater elbow adduction torque. The elbow adduction torque is needed to resist the elbow abduction stress that occurs during the arm-cocking phase. The American pitchers also exhibited 25-30% greater elbow and shoulder proximal forces during the arm acceleration phase which was associated with increased ball velocity (Stodden et al., 2006). The shoulder proximal force resulted from the force applied by the trunk to the upper arm at the shoulder and the elbow proximal force resulted from the force applied by the upper arm to the forearm at the elbow (Fleisig et al., 2009). These forces are needed to help resist shoulder and elbow distraction (Stodden et al., 2005). However, the greater forces and torques shown in American pitchers predisposed this group to a higher risk of injury to shoulder and elbow structures compared to the Korean pitchers. Based on these findings, it can be concluded that pitching mechanics varies between cultures which might due to the differences in training and coaching methodology. In addition, differences in anthropometric measures such as body height, body mass and the slightly greater arm length in American pitchers contributed to 10% higher ball velocity compared to the ball velocity obtained by Korean pitchers, with body mass being the only variable that contributed to the ability to predict ball velocity. Pitchers with larger body mass tended to throw the ball faster than those who weighed less. A larger athlete created larger forces as an indication of more strength (Werner et al., 2008). Computer
simulation models can be used to observe the effect on ball speed at release if segment strength is increased by 5%.

2.3.2.2 Proximal-to-Distal Sequential Motion and Timing Window

A number of authors have suggested that a proximal-to-distal sequencing in throwing is necessary to achieve maximal projectile speed or distance (Alexander, 1991; Herring and Chapman, 1992; Putnam, 1993; Vaughn, 1985). However, several computer simulation studies on overarm throwing techniques demonstrated that the optimal sequence of the arm motions varied as throwers’ physical characteristics and projectile mass varied (Chowdhary and Challis, 2001; De Lussanet and Alexander, 1997; Hirashima et al., 2002). Proximal-to-distal sequencing is defined as the motion which is initiated with the larger, heavier, slower central body segments; then, as the energy increases, the motion proceeds outward to the smaller, lighter and faster segments (Bunn, 1972). In the proximal-to-distal sequencing, the forward acceleration of the proximal segment plays an important role in causing the distal segment to lag behind. The following forward acceleration of the distal segment is essentially an outcome of the way the proximal segment interacts with the distal segment as a function of the proximal segment’s angular velocity. The proximal segment is subsequently slowed down mainly due to the motion-dependent effect of the distal segment on the proximal segment (Putnam, 1993).

Generating sequential movements closer in time may be advantageous up to a point; however generating sequential movements too close together in time would ultimately be disadvantageous, as it would lead to a loss of the sequencing effect and non-optimal exploitation of momentum transfer (Herring and Chapman, 1992; Stodden et al., 2005). The proximal-to-distal sequencing is often described in terms of the linear velocities of the segment endpoints, joint angular velocities or segment angular velocities. Explanations of segment motion sequences are dependent not only on knowledge of the joint torques driving the system of linked segments, but on the way the segments interact as functions of their motions and orientations.
Many factors associated with the timing and forces could affect ball speed. One factor that could affect ball speed is the peak hand translational speed which varies from throw to throw. The hand translational speed results from a complex series of motions, including rotation of the trunk and segment rotations at the shoulder, elbow and wrist. These motion rotations are produced by both active muscle contractions and passive effects (interaction torques) associated with motion at adjacent joints/segments (Feltner and Dapena, 1989; Herring and Chapman, 1992; Putnam 1993). Another factor that could affect ball speed is the timing of ball release. The elite pitchers consistently (with little variability) produce high ball velocity and try to avoid high joint loads at the shoulder and elbow to reduce injuries (Hore et al., 1995; Stodden et al., 2005). However, the ability to consistently generate an appropriate movement pattern with appropriate timing is a challenge for the pitchers.

**Proximal-to-Distal Sequencing**

Vaughn (1985) and Putnam (1993) explain the proximal-to-distal sequence of segment motion observed in overarm throwing. In the sequential motion, the more proximal segment endpoints reached maximum velocity first followed by the next most distal segment endpoints. It was also noted that the velocities of the segment endpoints declined rapidly after reaching peak velocities. As the proximal segment begins its forward motion, the next most distal free hinge segment momentarily lags behind. Based on the findings, while the forward linear velocity of the elbow begins a rapid increase 100 ms before release, the velocity of the wrist lags behind, and does not catch up to the elbow until 40 ms before release (Vaughn, 1985). In another study, Herring and Chapman (1992) used a three-segment model to examine proximal-to-distal sequencing when simulating an overarm throw in the sagittal plane. It was observed that the ball range and ball velocity at release were optimised when the onset of joint torques and time of peak joint angular velocities follows a proximal-to-distal sequence (Herring and Chapman, 1992).

Basically, the proximal-to-distal sequence of joint/segment rotations is produced by the proximal-to-distal sequential muscle activities. Chowdhary and Challis (2001) used a double-segment muscle-actuated planar model to observe proximal-to-distal sequencing in throws for maximum distance and in throws for maximum velocity.
throws for maximum distance, the activation of the wrist flexors was always after that of the elbow extensors which denoted that a proximal-to-distal sequencing of the muscle activation occurs. However, throws for maximum velocity did not always employ a proximal-to-distal sequencing. Instead, throws for maximum velocity was enhanced due to moment reversal. Moment reversal is defined as the moment at a joint changes its direction, for example changing from an elbow extending moment to an elbow flexing moment. The difference between throws for maximum distance and throws for maximum velocity is presumably due to the circumstances where the angle, height and velocity of ball at release influenced throws for maximum distance, whereas in throws for maximum velocity, the ball velocity at release is the sole factor (Alexander, 1991; De Lussanet and Alexander; 1997).

The results found by Chowdhary and Challis (2001) was supported by Hirashima et al. (2002) using surface EMG to investigate the activation patterns of the abdomen muscles (external oblique (lower right abdomen – left and right) and rectus abdominis (mid abdomen)) and muscles from the upper extremity (serratus anterior at the sixth rib, serratus anterior at the eight rib, anterior deltoid, pectoralis major, triceps brachii, pronator teres and flexor carpi ulnaris) by identifying the onset and peak times of the muscle activity. The sequential muscle activities from the scapular protractor (serratus anterior at rib 6) to the shoulder flexors (anterior deltoid and pectoralis major) were identified by onset time with the serratus anterior at rib 6 activated first. After the scapular protractors became activated, the shoulder flexors began their activity almost simultaneously. The sequential activity from the shoulder flexors to the elbow extensor (flexor carpi ulnaris, pronator teres and triceps brachii) was identified by onset time. The flexor carpi ulnaris, pronator teres and triceps brachii became activated almost simultaneously. The elbow extensor, wrist flexor and elbow pronator were activated at almost the same onset and peak times. The left external oblique became activated the earliest in the stride phase to help prevent the upper trunk from rotating together with the pelvis to face the target. The right external oblique became activated almost at lead foot stride. The rectus abdominis was at its peak just before ball release which contributes to the centripetal force required for the circular motion of the upper extremity. The findings indicated that
in throws for maximum speed, the muscles are not always activated in sequence from the lower to the upper parts of the body. However, using surface EMG in an experiment might cause muscle cross talk to occur when the EMG signal from one muscle interferes with that of another, limiting the reliability of the signal of the muscle being tested. In addition, surface EMG can only measure the outermost layer (superficial) muscles and it is hard to narrow down the signal to a single muscle.

It was observed that most studies used planar models to examine the segment interaction in overarm throwing whereas in reality, the movement is three-dimensional. For that reason, a three-dimensional torque-driven simulation model will be used to observe if the trunk, clavicle, shoulder and elbow follow the proximal-to-distal sequence for high velocity throws.

Timing Window
Apart from target velocity, target accuracy is another crucial goal in baseball pitching motion (Atwater, 1979; Calabrese, 2013). The factors affecting accuracy are the flight time of the ball which determines how far the ball drops due to gravity, the location in space where the ball is released, and the direction in which the ball is travelling at the time of release which depends on the direction of hand linear velocity and hand orientation. If the ball is released early, it goes high whereas if the ball is released late, it goes low (Hore et al., 1996). Therefore, the ball should be released within a certain amount of time which known as a timing window because outside of this window the ball will miss the target. It is important for the pitcher to know the timing window for ball release so that it can give some flexibility in timing which allows close attainment of the objective in repeated throws where small errors in timing are made (Herring and Chapman, 1992). However, it is hard to compare between studies because of different definitions of accuracy, target size, and target distance.

The timing window for ball release is dependent on the timing of muscle activation and there is a subtle interaction between the timing window for ball release and the timing of muscle activation. Therefore, it is crucial to consider both the timing window for ball release and the timing of muscle activation when examining
A two-segment muscle-actuated model was used to investigate the optimal solution which gave the most accurate throw with the shortest flight time. The interval between the onset of wrist activation and elbow extensor activation was referred to as a proximal-to-distal delay. The time of ball release was the time duration from the initiation of movement until ball release. For one set of simulations, to hit the target at 8 m, the optimal throw was achieved with a time delay between the onset of wrist activation and elbow extensor activation of 49 ms and the time of ball release of 83.4 ms. At this optimal point in the solution space, the timing window was 1.2 ms. The timing during which the wrist flexors could be activated was 10.41 ms. At a proximal-to-distal delay of 54.5 ms the timing window for ball release was much larger, 7.2 ms. However, errors of this magnitude in proximal-to-distal delay and the time of ball release cannot be accommodated if they occur simultaneously because it might cause major inaccuracies of the throw (Seroyer et al., 2010). In order to ensure that all throws hit the target when there are errors in the time of ball release and in the timing of muscle activation, 4 ms in proximal-to-distal delay and a timing window for ball release of 2.4 ms are permissible. However, much larger errors in either muscle activation or the ball release time could still lead to a successful throw, as long as both criteria did not occur together. However, Chowdhary and Challis (2001) only consider the general throw of projectile, hence the results of the simulation model cannot be applied directly to real throwing as in baseball pitching which involves more muscles and where the interactions between segments are more complicated.

Jegede et al. (2005) used 15 right-handed recreational baseball players to observe variability in the timing of ball release for fast and accurate throws in baseball pitching. The subjects were divided into two categories, skilled and unskilled depending on their experience in baseball. It was observed that the mean timing window for ball release was 28 ms for unskilled throwers and 7 ms for skilled throwers. Unskilled throwers showed a strong relationship between ball speed and the timing of ball release, but not in skilled throwers which is apparently due to the difference in variability of the timing of ball release. Conversely, skilled throwers showed a strong relationship between ball speed and peak forearm angular velocity.
compared to the relationship between hand angular velocity and ball speed. Thus, it can be concluded that the relationship between ball speed and the timing of ball release is dependent on skill level.

2.3.2.3 Mound vs Flat-ground Pitching

Flat-ground throwing has been part of baseball rehabilitation and conditioning for decades. For pitchers, the flat-ground throwing phase of the interval throwing program is followed by throwing off the mound, progressing from partial-effort to full-effort pitches. The progression of throwing phases from flat-ground throwing to throwing off the mound allows an injured athlete to gradually recover arm flexibility, arm strength, and proper throwing mechanics (Fleisig et al., 2011). Long-distance flat-ground throwing requires the pitcher to generate force, torque, range-of-motion, and speed higher than throwing off the mound which is the advantageous manner (Fleisig et al., 2011) to train a pitcher to have greater arm strength, arm flexibility, arm speed and ball speed. The benefit of throwing off a mound is that the pitcher is able to alter the release point of the ball to develop an appropriate ball trajectory (Rash and Shapiro, 1995).

Fleisig et al. (2011), Nissen et al. (2013) and Slenker et al. (2014) examined the differences in pitching mechanics between pitcher throwing from flat-ground and pitcher throwing off the mound. It was found that the timing between maximum upper arm external rotation to maximum upper arm internal rotation, the time between maximum upper arm internal rotation to ball release and the time between maximum upper arm external rotation to ball release remained the same for the two conditions. However, the time taken from foot contact to maximum upper arm external rotation and ball release was shorter for the mound condition (Nissen et al., 2013). The pitcher’s stride length was slightly less when throwing from flat ground (1.12 m) compared with the mound (1.14 m); however this difference was not statistically significant. The differences between shoulder joint torque and elbow joint torque were small in each condition (1.9 Nm at each joint, or 6% greater on the mound (Nissen et al., 2013; Slenker et al., 2014). Ball speed at release thrown from the mound (23.5 ± 2.8 m/s) was not much different to the ball speed thrown from
flat-ground (23.3 ± 2.8 m/s) (Nissen et al., 2013; Slenker et al., 2014). In addition, studies by Badura et al. (2003) and Milewski et al. (2012) show there were no kinematic differences in the hip and knee joints between throwing from the mound or flat-ground.

2.3.3 Three-dimensional Computer Simulation Models

Developing a computer simulation model includes the procedures of defining the problem, deriving the equations of motion, writing the computer program, determining input values, validating the model, and performing simulation experiments (Vaughan, 1984). The application of computer simulation models to sporting activities can provide a deeper insight into the mechanics of human movement (Yeadon and King, 2008). It can also answer the ‘what if?’ questions which are difficult to address by experimental studies or descriptive analysis. This provides a safe means to investigate the optimisation of sports performance without actually having an athlete try out a new technique. Additionally, computer simulation models are able to help understand the factors that limit optimal performance or factors that might affect loading on the body (King, 2011).

Despite all advantages and potential in using computer simulation models in movement research, there are some limitations and drawbacks. Panjabi (1979) argued that a mathematical model was only a set of equations predicting behaviour in unknown situations and that no perfect validation was possible. Yeadon et al. (1990) demonstrated that a model could be evaluated by taking input data from a real performance and comparing the simulation output with actual performance.

Vaughan (1984) further recognised two other drawbacks: advanced knowledge in mathematics and computer simulation is required, and that results are often difficult to translate to practicality. With the advancement in information technology and commercially available simulation package such as ADAMS and AUTOLEV, there has been increased use of simulation models. In this section, three-dimensional models of overarm throwing in fastball pitching will be reviewed and analysed.
Theoretical studies using two-dimensional models of overarm throwing have been mentioned elsewhere in this chapter.

Feltner and Dapena (1986; 1989) developed a three-dimensional double-segment model to examine the interactions between segments of the throwing arm in baseball pitching. The findings indicated that maximum upper arm external rotation resulted from the actions of the shoulder flexor and shoulder extensor. The elbow adduction torque was closely related to the internal rotation joint torque at shoulder. The elbow adduction torque served to maintain the integrity of the elbow joint as the upper arm was externally rotated to its position of maximum external rotation while it was subsequently internally rotated prior to ball release. The rapid forearm extension prior to ball release was due primarily to the trunk twist that occurred during the pitch, and not to the actions of the elbow extensor muscles. This result was in agreement with a study done by Naito and Maruyama (2008). However, the limitation of the study by Feltner and Dapena (1986; 1989) was that it only explains the interaction between two-segments – the upper arm and forearm.

Hong et al. (2001) developed a six-segment model to observe the mechanics and the muscular coordination of fastball pitching. The six-segment model comprised the pelvis, the upper trunk which is a combination of the three segments; head, upper part of the trunk and middle part of the trunk, the upper arms, and the forearms which were modelled as a combination of forearm and hand. Hong et al. (2001) found that the upper trunk twist played a key role in ball speed. In addition, the joint torque induced by motion of the upper trunk segment helped the elbow extensor in slowing flexion and producing rapid forearm extension near ball release. They also found that the contribution of the non-throwing upper limb was minimal and variable. However, since the forearm and hand was modelled as one segment, the contribution of the wrist to the ball speed was neglected in the study.

Fuji and Hubbard (2002) develop a four-segment three-dimensional simulation model to investigate the relationships between optimal movement and muscular strength in baseball pitching. Six torque-generators were included at shoulder, elbow and wrist which had torque-angle and torque-angular velocity characteristics of Hill-
type muscle function. The agonist/ antagonist muscle groups were modelled as one
torque generator. The inverse dynamics method was used to calculate the total joint
torque. The model was validated by matching the release velocity, joint loading and
inaccuracy using the following equation,

\[ J = w_1 \times (velocity) - w_2 \times (inaccuracy) - w_3 \times (joint loads) \] (2.1)

where \( w_1, w_2 \) and \( w_3 \) are weightings in the objective function score \( J \). The velocity
term was the resultant ball speed at release which defined as the instant when speed
reached maximum. To calculate the inaccuracy, a target was located 19.44 m from
the pitcher’s standing location. The target was a circle with 1 meter in diameter and
aligned 1 meter above the ground. The inaccuracy was then calculated as the
squared distance from the ball to the centre of the circle when the ball reached the
circle. The joint-loads were referred to a dimensionless sum of contributions from
all joints which were calculated using Equation 2.2:

\[
\text{Joint loads} = \sum_{i=1}^{6} \left( \frac{P_{T_i}^{\text{peak}} - P_{T_i}^{\text{threshold}}}{P_{T_i}^{\text{threshold}}} \right)^2 + \sum_{j=1}^{3} \left( \frac{C_{T_j}^{\text{peak}} - C_{T_j}^{\text{threshold}}}{C_{T_j}^{\text{threshold}}} \right)^2
\] (2.2)

where \( P_{T_i}^{\text{peak}} \) = peak passive torque and \( C_{T_j}^{\text{peak}} \) = peak constraint torque.

From the study, Fujii and Hubbard (2002) found that the weighting coefficient for
joint load had a strong influence on the matching simulation. The pitching motion
became more similar to the actual performance as the joint load coefficient
increased. However, the limitation of their study was that the ball was fixed at the
Metacarpophalangeal joint and it was assumed that the ball did not roll forward to
the fingertips before release. In addition, the simulation and optimisation were only
used to reproduce the pitching performance without any initiative to optimise the
performance.

The pattern of upper arm abduction about the upper trunk is fairly constant between
90° and 110° from front foot contact to ball release because this angle is believed to
maximise ball speed and reduce stress on the throwing arm (Atwater, 1979). Based
on these findings, Matsuo et al. (2002) investigated the effects of upper arm abduction angle on ball velocity and on the injury-related joint kinetic variable using a three-segment model. A three-segment model was composed of the hand with the ball, the forearm, and the upper arm. Due to limitations in the computer resolution of the video image, the mass of the hand holding the ball was assumed to be at the same position as the wrist before the instant of ball release. As a consequence, maximum wrist velocity was used as an approximation of ball velocity. From the experimental analysis, the upper arm abduction angle at ball release for the actual motion was 95.9° (± 15.7°) for all pitchers and ranged from 70° to 119°. The mean upper arm abduction for the overhand and three-quarter-hand pitchers was 101° ± 13°. It was found that the upper arm abduction angle of 90° did not always maximise wrist velocity nor minimise elbow adduction torque. On the other hand, the computer simulation result indicated that upper arm abduction angle clearly affected wrist velocity (Matsuo et al., 2002; Stodden et al., 2006) and that the most effective upper arm abduction angle for wrist velocity depended on the individual pitcher but was scattered around 90° (in the range between 85° to 110°). The limitation of the study was that in the model, Matsuo et al. (2002) assumed the mass of the hand holding the ball to be at the same position of the wrist. This might have affected the computer simulation result.

Hirashima et al. (2008) used an induced acceleration analysis to investigate the contribution of joint torque and velocity-dependent torque on each joint angular acceleration during baseball pitching. A four-segment model comprised trunk, upper arm, forearm, and hand plus ball was developed. It was found that the proximal segment motions, as for example trunk forward tilt, trunk lateral tilt, and upper arm internal rotation, were mainly accelerated by the joint torques at their own joints, whereas the distal segment motions such as forearm extension and hand flexion were mainly accelerated by the velocity-dependent torques. The angular velocities of the trunk and upper arm were the main source to produce the velocity-dependent torque for initial forearm extension acceleration. As a result, the elbow joint angular velocity increased, and at the same time, the forearm angular velocity relative to a global frame also increased. The elbow angular velocity subsequently accelerated the forearm extension and hand flexion. It also accelerated the upper arm internal
rotation at the instant of ball release. However, the limitation of using induced acceleration analysis in the study was that the number of segment of the model affects the interpretation of the function of joint torques. In other words, induced acceleration analysis might not give an accurate result if the number of segment in the model increases.

Using a seven-segment model, Naito et al. (2011) investigated the momentum produced by the individual joint moments or joint forces in throwing. The joint moments were classified into their muscular and non-muscular interactive moments in order to assess their contribution to the generation of momentum. A seven-segment model consisted of the trunk, right upper arm, right forearm, right hand, left upper arm, left forearm and left hand. The pitching mound was set to a height of 15 cm from the floor of the gym, and the target was located at a position 5 m away from the pitching rubber on the mound. Since the position of pitcher’s mound from home plate in real competition is about 18 m, placing the target 5 m away from the pitching rubber might miscalculate the kinematic and kinetic parameters. The maximum resultant velocity at the distal endpoint (MP joint) of the throwing hand was used to measure the pitched velocity of each trial and to estimate the ball release time. One frame (0.004 sec) after that velocity was assumed to be at the instant of ball release. Measuring the velocity in this manner might underestimate the value of the ball speed. The results showed that the velocity of the distal endpoint of the throwing hand was primarily produced by the trunk extension/flexion and trunk twist. The contribution of the upper arm external/internal rotation to the hand velocity was relatively small. Naito et al. (2011) concluded that the trunk flexor and rotator muscle power generated in an earlier phase of pitching are the primary source of the arm acceleration. In addition, the centrifugal-effect transfer the momentum from the proximal segment to the distal-end plays a critical role in enhancing the distal arm velocity.

The forearm pronation occurred as a part of the natural, high velocity throwing pattern rather than as a means of intentionally applying spin to the ball. Since the elbow joint is fully extended at release, perhaps a ‘natural and safe’ way to reduce the high velocity that the hand possesses as the ball is released is to allow the hand
and arm to ‘roll’ forward, downward, and outward by using radioulnar pronation and upper arm extension that occurs after release (Atwater, 1979). Based on these assumptions, Naito et al. (2014) used a seven-segment three-dimensional model to measure the factors that contributed to forearm pronation. The results indicated that forearm pronation is mainly propelled passively by scapula adduction/abduction and upper arm adduction/abduction, rather than pronation muscular torque. However, the kinetic response from scapula segment was not included in the model which can mislead the result obtained. Additionally, in the model the ball was placed at the metacarpophalangeal joint, which is more proximal than the fingertip, to determine the distal endpoint velocity. This measurement could relate to underestimation of the pitched velocity in the study, because contribution of finger’s interphalangeal joint extension, which can apply 2.88 ± 2.61 m/s of velocity to ball were excluded from the method.

2.4 Summary of Literature

In this chapter, literature relating to experimental studies involving fastball pitching was described. Theoretical studies were also outlined and reviewed. The literature was then summarised with particular consideration of those issues relevant to the construction of a computer simulation model of overarm throwing and subsequent analysis of technique. While the theoretical research studies provided some insight into the mechanics of the movement, they generally over-simplified the shoulder complex and therefore the role of this segment to the ball speed is still not well understood. A three-dimensional torque-driven model will not only be more applicable to the current baseball pitching but will also allow findings from previous studies to be verified.
CHAPTER 3
KINEMATIC ANALYSIS

3.1 Introduction

Kinematic data of overarm throwing were collected from an elite fastball pitcher. This chapter describes the protocol used to collect the data and also explains the processing and analysis of the data.

3.2 Data Collection

The data collection took place in the Biomechanics laboratory. Vicon Motion Analysis System (1.7.1) was used to collect the kinematic data of a fastball pitcher (age: 28 years, mass: 89.8 kg, height: 1.89 m). He was a member of a baseball regional team in the UK. The pitcher performed a two-seam fastball pitch (Figure 3.1).

Figure 3.1: The fastball pitching action.
3.2.1 Data Collection Set-up

16 Vicon MX13 cameras, sampling at a frequency 300 Hz, were used to track the motion of markers attached to the subject and the ball. Vicon system was chosen because it had the lowest RMS errors as well as having a low tracking and editing time (Richards, 1999). 300 Hz was chosen because it is fastest possible for the number of markers used. This selection of frequency has been used in previous research on cricket fast bowlers (Felton, 2014) successfully. A portable baseball practice net with a strike zone in the centre was located at the end of the laboratory. The distance between the subject and the strike zone was 11.5 m. The cameras were positioned and focused on the pitching action (Figure 3.2).

The calibration protocol which has been successfully carried out in previous studies (Jackson, 2010; Kentel, 2009) was applied in this study. Before motion capture, two stages of calibration, static and dynamic, were performed. In the static calibration, a calibration object was placed in the calibration volume and the system captured the position data of the markers on it. In dynamic calibration, another calibration object, a wand, was moved through the calibration volume. In both cases, the relative positions of the markers with respect to each other, which were known previously, were compared with the captured data and the error for each camera was calculated. The calibration errors of each camera used in this were under ± 0.3 mm.

In addition, a video camera HDC-TM900 captured at 1080/50p (1080 lines of resolution, 50 frames per second) was set up on the right side of the throwing direction (Figure 3.2) to aid in visual reference. A schematic showing the positions of the cameras, throwing area and strike zone is given in Figure 3.2.
Figure 3.2: Schematic of experimental set-up; light grey arrows represent Vicon cameras and dark grey arrows represents video camera (figure not drawn to scale).

Forty-seven 14 mm retro-reflective markers (Appendix H) were attached to the subject’s body (Figure 3.3); forty-three markers were attached on bony landmarks in accordance with the marker set developed by Worthington (2010) and a band with four retro-reflective markers was placed on the head of the subject (Felton, 2014).
In order to calculate the moment of ball release and ball release velocity, four reflective tapes were attached on both sides of the ball (Figure 3.4).

Figure 3.3: Subject with retro-reflective markers.

Figure 3.4: Ball with reflective markers.
3.3 Protocol

The data collection procedures were explained to the subject in accordance with the Loughborough University ethical guidelines and an informed consent form was signed. The subject performed a step-by-step stretching and warm-up, similar to that performed at a training session. Subsequently, the subject was asked to perform full-effort two-seam fastballs from flat-ground toward a strike zone. A trial was considered to be successful if the equipment was triggered correctly, the subject threw for strikes with maximum effort and less markers loss during the delivery. From the performance, 15 successful trials had been captured.

3.4 Anthropometric Measurements

Ninety-five anthropometric measurements of the participant were taken to determine the segmental inertia parameters required as the inputs to an inertia model developed by Yeadon (1990a). The measurements comprised 34 lengths, 41 perimeters, 17 widths and 3 depths which were taken by a skilled researcher (Appendix D). Total body mass was measured and used in the calculation of segmental inertia parameters. The segmental inertia parameters were used in the angle-driven model and torque-driven model.

3.5 Segmental Motion Analysis

The fifteen best fastball pitching trials (Appendix A), with the highest ball velocity were selected and manually labelled within Vicon’s Nexus software. Subsequently, Vicon BodyBuilder software was used to construct a number of segments in order to calculate segmental motion data from the marker trajectories. The Cardan sequence of rotations at each joint was XYZ (Figure 3.5). The Cardan rotation sequence XYZ is often used in biomechanics (Cole et al., 1993). An eight-segment right-handed pitcher model was formed by using the markers attached to the subject. The pitcher
model comprised pelvis, trunk plus head (which is referred as upper trunk in the whole thesis), scapula segment, right upper arm, right forearm, right hand, left upper arm and left forearm plus hand.

Initially, a reference frame was set on each segment to measure its orientation. In order to be consistent within the model and to visualize rotation angles easily, all reference frames were set in the same way: +x, pointing to the right or lateral side of the segment; +y, pointing to the segment’s front (throwing direction); +z, pointing from the bottom to the top or from proximal end to distal end (Figure 3.5).

Figure 3.5: Global coordinate system with unit vectors $\hat{i}$, $\hat{j}$ and $\hat{k}$ in the directions of axes $x$, $y$ and $z$ (adapted from Robertson et al., 2014).

To estimate the orientation of the anatomical rotation axes and segmental link lengths of the segment, joint centre locations were required. The marker set chosen (Appendix H) and the calculations defining the segments followed the descriptions of Zatsiorsky (1998) and Robertson et al. (2014).

For the first segment, pelvis orientation was calculated relative to the global reference system (GRS) (Kim et al., 2010; Robertson et al., 2014; Zatsiorsky, 1998)
using four markers attached to the subject’s pelvic girdle at the left posterior superior iliac (LPSI), right posterior superior iliac (RPSI), left anterior superior iliac (LASI) and right anterior superior iliac (RASI). Initially, the origin/midpelvis (Figure 3.6) was determined to be midway between $\vec{P}_{RASI}$ and $\vec{P}_{LASI}$ and was calculated as follows,

$$\vec{O}_{PELVIS} = 0.5 * (\vec{P}_{RASI} + \vec{P}_{LASI}) \quad (3.1)$$

To create the $x$-component (or lateral direction) of the pelvis, a unit vector $\hat{i}$ was defined by subtracting $\vec{O}_{PELVIS}$ from $\vec{P}_{RASI}$ and dividing by the norm of the vector:

$$\hat{i} = \frac{\vec{P}_{RASI} - \vec{O}_{PELVIS}}{|\vec{P}_{RASI} - \vec{O}_{PELVIS}|} \quad (3.2)$$

Subsequently, a unit vector was created from the midpoint of $\vec{P}_{RPSI}$ and $\vec{P}_{LPSI}$ to $\vec{O}_{PELVIS}$ yielding:

$$\hat{v} = \frac{\vec{O}_{PELVIS} - 0.5*(\vec{P}_{RPSI} + \vec{P}_{LPSI})}{|\vec{O}_{PELVIS} - 0.5*(\vec{P}_{RPSI} + \vec{P}_{LPSI})|} \quad (3.3)$$

Using the right-hand rule, a unit vector normal to the plane containing $\hat{i}$ and $\hat{v}$ was computed from a cross product to create a unit vector $\hat{k}$ in the direction of the $z$-axis (Equation 3.4).

$$\hat{k} = \hat{i} \times \hat{v} \quad (3.4)$$

The anterior unit vector $\hat{j}$ was calculated similarly which yields

$$\hat{j} = \hat{k} \times \hat{i} \quad (3.5)$$

1.073.6
Next, the rotation matrix was calculated as in Equation (3.6) describing the orientation of the pelvis.

\[
R_{PELVIS} = \begin{bmatrix}
\hat{i}_x & \hat{i}_y & \hat{i}_z \\
\hat{j}_x & \hat{j}_y & \hat{j}_z \\
\hat{k}_x & \hat{k}_y & \hat{k}_z
\end{bmatrix}
\] (3.6)

Since the orientation of pelvis is relative to a global frame, it needs to be expressed in the local coordinate system by taking transpose of matrix \(R_{PELVIS}\) (Zatsiorsky, 1998) which yields

\[
R_{PELVIS} = \begin{bmatrix}
\hat{i}_x & \hat{j}_x & \hat{k}_x \\
\hat{i}_y & \hat{j}_y & \hat{k}_y \\
\hat{i}_z & \hat{j}_z & \hat{k}_z
\end{bmatrix}
\] (3.7)

For the second segment, the upper trunk rotates about the midpelvis (the origin) (Figure 3.7). To calculate the upper trunk orientation, another four markers namely CLAV, STRN, C7, and T10 vertebrae were used (Robertson et al., 2014). Upper thorax was calculated as the midpoint between C7 and CLAV. Lower thorax was calculated as the midpoint between T10 and STRN. Front thorax was calculated as
midpoint between STRN and CLAV. Back thorax was calculated as midpoint between C7 and T10. The line vector drawn from midpoint of the pelvis markers to midpoint of the thorax markers was used as the Z (longitudinal) axis of the trunk frame. The anteriorly directed line vector perpendicular to the plane formed by the pelvis midpoint and the thorax markers was used as the Y (anteroposterior) axis of the trunk. The X (lateral) axis is perpendicular to the Z and Y axis (Kim et al., 2010). The rotation matrix describing the orientation of the upper trunk is

\[
R_{U.TRUNK} = \begin{bmatrix}
\hat{i}_x & \hat{i}_y & \hat{i}_z \\
\hat{j}_x & \hat{j}_y & \hat{j}_z \\
\hat{k}_x & \hat{k}_y & \hat{k}_z
\end{bmatrix}
\] (3.8)

A segment was created to estimate the clavicular motion. For simplicity, the right and left scapula were assumed to comprise a single segment to represent the movement of shoulder girdle. The clavicular motion was calculated based on the rotation of the right scapula about the upper trunk (Figure 3.7) using five markers (C7, clavicle (CLAV), right shoulder anterior (RSHOA), right shoulder posterior (RSHOP), and T10) (Veeger et al., 1993; Van Der Helm and Pronk, 1995). The Z (longitudinal) axis and the Y (anteroposterior) axis for the scapula are the same as the Z (longitudinal) axis and the Y (anteroposterior) axis of the trunk frame. The X (lateral) axis is defined in the direction between the upper thorax and the midpoint of RSHOA and RSHOP. The Z (longitudinal) axis for the upper arm is defined from the midpoint of RSHOA and RSHOP to the midpoint of RELBM and RELBL. The X (lateral) axis of the upper arm is perpendicular to midpoint of RSHOA and RSHOP. The Y (anteroposterior) axis of the upper arm is perpendicular to the Z (longitudinal) axis and the X (lateral) of the upper arm. The Z (longitudinal) axis for the forearm is defined from the midpoint of RELBM and RELBL to the midpoint of RWRA and RWRB. The X (lateral) axis of the forearm is defined to be in the direction of RELBM to RELBL. The Y (anteroposterior) axis of the forearm is perpendicular to the Z (longitudinal) axis and the X (lateral) of the forearm. The Z (longitudinal) axis for the hand is defined from the midpoint of RWRA and RWRB to the RHND. The X (lateral) axis of the hand is defined to be in the direction of RWRB to RWRA. The Y (anteroposterior) axis of the hand is perpendicular to the Z
(longitudinal) axis and the X (lateral) of the hand. The left arm was calculated in the same manner as the right arm.

The calculation of segment orientation and rotation matrices were the same as explained for upper trunk orientation (Equation 3.8).

Figure 3.7: Reference frames attached to the body segments (pelvis, upper trunk, scapula, right upper arm, right forearm, right hand, left upper arm, left forearm and left hand) and ball when seen from the front of the subject

The Cardan-Euler angles (Section 4.5) between the proximal and distal segment reference frames were computed to obtain relative rotation angles. The sequence of rotations in the sagittal (x), coronal (y) and the transverse (z) planes was used in the calculations. The neutral positions of all segments were chosen to be the anatomical position of the pelvis, trunk plus head, scapula and upper limbs (Appendix E).
3.6 Splining the Data

The angle-driven simulation model was driven by joint angle time histories obtained from recorded performances. Quintic splines (Wood and Jennings, 1979) were fitted to the joint angle time histories in order to enable each joint angle to be used as an input to the simulation model at different time steps during the simulations. Quintic splines produced six coefficients for each time step which were then read by the simulation model and used to calculate the angle, velocity and acceleration at each integration time step.

Additionally, a quintic spline smooths the angle data to remove noise due to marker movement as a result of soft tissue, marker movement or errors in the tracking of markers. The level of smoothing is important as it must remove noise whilst keeping as much of the genuine signal.

During the fitting process, a pseudo data set was generated by averaging data values from adjacent time frames. The error estimate at each data point was calculated from the difference between the real and pseudo data (Yeadon, 1990b; King, 1998) using a weighted combination of the local and global error variance. In order to obtain a balance between removing noise and over-smoothing, equal weighting at each data point was used for error estimate variance; 50% local error and 50% global error. For all angles the average errors were less than 0.2°. Raw and splined rotation angle time-histories and middle pelvis displacement time-histories of Trial 20 can be seen in Figures 3.8 – 3.10. Trial 20 was chosen because it was one of the best trials obtained. Ball release was at time zero. Upper trunk rotates at midpelvis, scapula segment rotates at suprasternal, upper arm rotates at shoulder, forearm rotates at elbow and hand rotates at wrist (Figure 3.7).
Figure 3.8: Raw (dotted line) and smoothed (solid line) translation of the midpelvis (left) and orientation angles of the upper trunk (right).
Figure 3.9: Raw (dotted line) and smoothed (solid line) orientation angles of the scapula (left) and right upper arm (right).
Figure 3.10: Raw (dotted line) and smoothed (solid line) orientation angles of the right forearm (left) and right hand (right).
3.7 Discussion

The in-vivo measurements of the motions of the scapula and clavicle are very difficult to quantify. Most studies on the motions of the shoulder mechanism i.e. (thorax, clavicle, scapula, and humerus) which connect the trunk and upper extremity were generally limited to unidimensional movements or positions, whereas three-dimensional studies on the motions of the shoulder mechanism are scarce. Due to the difficulties in three-dimension motion of the shoulder mechanism, models of the shoulder mechanism have been limited, which is mainly been based on the use of simplified (two-dimension) models. Many investigators disregard the motion of the scapula and clavicle and limit the study to the movement of the humerus with regard to the trunk. To overcome this difficulty, a simple representation needs to be used to describe the motion of the shoulder mechanism in overarm throwing specifically in fastball pitching. A segment called the scapula segment which rotates about the suprasternal notch was formed (Veeger et al., 1993; Van Der Helm and Pronk, 1995). The movement of this segment is described relative to the trunk (Poppen and Walker, 1976).

The orientation angles of this study are in accordance with the angles found by Feltner and Dapena (1986), Fujii and Hubbard (2002) and Hong et al. (2001). On average, the angle of the forearm in adduction/abduction in a static position is about 11° (Amis and Miller, 1982). Since baseball pitching motion involves a fast speed dynamic movement, the data of the forearm adduction/abduction produced from the experiment are considered realistic.

3.8 Summary

In this chapter, the collection and processing of the performance data of overarm throwing performed by an elite fastball pitcher has been described. The next chapter will discuss the development of the angle-driven simulation model.
CHAPTER 4

DEVELOPMENT OF ANGLE-DRIVEN SIMULATION MODEL

4.1 Introduction

This chapter describes the development of the eight-segment angle-driven model which will be used to simulate the overarm throwing performance. An angle-driven model is a model which is driven using the kinematics from an actual performance. Using an angle-driven model means the joint angles (which will also be referred to as segment name throughout the thesis) are predetermined and therefore the technique is very close to that actually used. The model comprised a pitcher and a ball attached at the distal end of the hand. This chapter consists of a general description of the angle-driven model along with any assumptions and simplifications. At the end of the chapter, a description of how to determine the complexity of the torque-driven model is given.

4.2 General Description of the Eight-Segment Angle-Driven Model

Considering previous studies which indicated that peak knee extension of the lead leg has less of a role in transferring energy from lower limb to the ball (Milewski et al., 2012) and that pitchers rely more on energy created in the core and upper extremity (Laudner et al., 2010), it was decided to exclude a direct representation of the lower limbs from the angle-driven and torque-driven model (Chapter 5). Instead the movement of the lower limbs was included by constraining the pelvis to translate in the same way as the recorded performances. The pitcher was modelled in three-dimensions using eight rigid segments to represent the pelvis, the trunk plus head (which will subsequently be referred to as upper trunk), the scapula, the throwing
the pitch arm (upper arm, forearm and hand) and non-throwing arm (upper arm and forearm plus hand) (Figure 4.1). Each of the rigid segments had mass, length and moment-of-inertia (Table 4.1), such that they represented the body segments of the pitcher.

**Figure 4.1**: Segments used within the simulation model.

The following features were used within the pitcher model and are shown in Figure 4.1:

- The shoulder girdle was modelled as one rigid segment (the scapula) to represent clavicular motion. The clavicular motion was calculated based on the rotation of the right scapula about the trunk.
- The right pelvis is also referred as right hip and the left pelvis is also referred as left hip.
- The trunk and head is assumed as one segment which is referred as upper trunk in the whole thesis.
• A damped linear spring was used to represent the force between hand and ball.
• The left forearm and left hand is assumed as one segment

The neutral positions of all segments were chosen to be the anatomical position of the pelvis, trunk plus head, scapula and upper limbs (Appendix E).

20 orientation angles were considered in the model (Figure 4.2): hand extension/flexion \( \theta_{WA} \), hand radioulnar deviation \( \theta_{WB} \), forearm extension/flexion \( \theta_{EA} \), forearm adduction/abduction \( \theta_{EB} \), forearm pronation/supination \( \theta_{EC} \), scapula elevation/depression (abduction/adduction) \( \theta_{SGB} \), scapula external/internal rotation \( \theta_{SGC} \), right upper arm flexion/extension \( \theta_{SA} \), right upper arm adduction/abduction \( \theta_{SB} \), right upper arm external/internal rotation \( \theta_{SC} \), upper trunk extension/flexion \( \theta_{TA} \), upper trunk medial/lateral tilt (abduction/adduction) \( \theta_{TB} \), upper trunk twist (external/internal rotation) \( \theta_{TC} \), pelvis forward/backward tilt \( \theta_{PA} \), pelvis adduction/abduction \( \theta_{PB} \), pelvis external/internal rotation \( \theta_{PC} \), left upper arm flexion/extension \( \theta_{FSA} \), left upper arm adduction/abduction \( \theta_{FSB} \), left upper arm external/internal rotation \( \theta_{FSC} \) and left forearm extension/flexion angle \( \theta_{FEA} \). In addition to the orientation angles, three translations at midpelvis were considered: translation in x-axis \( \delta_{PA} \), translation in y-axis \( \delta_{PB} \) and translation in z-axis \( \delta_{PC} \). Details of the axes of movement of the orientation angles can be found in Appendix E.
Figure 4.2: The simulation model representing the pitcher showing twenty orientation angles for each joint and three linear translations at midpelvis.

The simulation model representing the pitcher (Figure 4.1 and Figure 4.2) was used within subject-specific angle-driven and torque-driven (Chapter 5) simulation models. The angle-driven model was driven with joint angle time-histories obtained from recorded performances, and hence the technique was very close to that actually used. The angle-driven model was developed to determine the hand-ball interaction and to ensure that the torque-driven model was sufficiently complex to simulate overarm throwing.

Additionally, the angle-driven model will be used to determine voluntary torque values as initial estimates for the torque-driven model. Throughout an angle-driven simulation model, the movement of the pitcher was driven by joint angle time-histories obtained from the kinematic motion analysis (Section 3.5). The outputs of the model include the force resulting from hand-ball interaction, joint torque time histories, the displacement of the distal end of each segment (Figure 4.7 – Figure
4.14), linear velocity of the distal end of each segment throughout the simulation and the velocity of the ball at release (Figure 4.7 – Figure 4.14). From the kinematic data, joint angle time-histories and their first two derivatives (angular velocity and angular acceleration) of the segments were obtained by fitting the original joint angle data with quintic splines (Wood and Jennings, 1979).

### 4.3 Inertia Parameters

#### 4.3.1 Body Segmental Inertia Parameters

The body segmental inertia parameters were calculated using the geometric model of Yeadon (1990a). Ninety-five anthropometric measurements were taken from the subject by an experienced researcher. The inertia model used the segmental density values taken from Dempster (1955) which are in preference to those obtained in the cadaver studies of Clauser et al. (1969) and Chandler et al. (1975). These segmental density values were subsequently scaled so that there was agreement between the measured mass of the pitcher and the mass determined by the inertia model.

The value of segmental mass, distance of centre-of-mass (CM) from proximal joint and moment-of-inertia about the lateral ($I_x$), frontal ($I_y$) and longitudinal ($I_z$) axes of the segments are shown in Table 4.1.
Table 4.1: Segmental inertia parameters calculated from the inertia model

<table>
<thead>
<tr>
<th>Segment</th>
<th>Mass (kg)</th>
<th>CM from proximal joint (m)</th>
<th>$I_x (kgm^2)$</th>
<th>$I_y (kgm^2)$</th>
<th>$I_z (kgm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>12.129</td>
<td>0.096</td>
<td>0.082</td>
<td>0.141</td>
<td>0.139</td>
</tr>
<tr>
<td>Trunk</td>
<td>37.766</td>
<td>0.310</td>
<td>1.340</td>
<td>1.501</td>
<td>0.436</td>
</tr>
<tr>
<td>Head</td>
<td>5.025</td>
<td>0.118</td>
<td>0.025</td>
<td>0.025</td>
<td>0.016</td>
</tr>
<tr>
<td>Chest</td>
<td>15.172</td>
<td>-0.091</td>
<td>0.124</td>
<td>0.196</td>
<td>0.185</td>
</tr>
<tr>
<td>Right upper arm</td>
<td>2.518</td>
<td>0.126</td>
<td>0.019</td>
<td>0.019</td>
<td>0.003</td>
</tr>
<tr>
<td>Right forearm</td>
<td>1.280</td>
<td>0.107</td>
<td>0.007</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>Right hand</td>
<td>0.326</td>
<td>0.084</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>Left upper arm</td>
<td>2.413</td>
<td>0.123</td>
<td>0.018</td>
<td>0.018</td>
<td>0.003</td>
</tr>
<tr>
<td>Left forearm</td>
<td>1.317</td>
<td>0.111</td>
<td>0.007</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>Left hand</td>
<td>0.374</td>
<td>0.079</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

4.4 Modelling the contact between the hand and ball

The contact between the hand segment and the ball was modelled using linear massless springs in x-axis, y-axis and z-axis. The force in the springs was dependent on the displacement and velocity of the springs. The forces in the springs were defined by:
\[ F = -kx - b\dot{x} \]  \hspace{1cm} (4.1)

Where:

- \( F \) = total forces in spring
- \( k \) = stiffness coefficient
- \( b \) = damping coefficient
- \( x \) = stretch/depression
- \( \dot{x} \) = velocity

The role of the linear springs was to hold the ball in place and limit the movement. The coefficients (stiffness \((k)\) and damping \((b)\) parameters) were both set to 1000 Nm\(^{-1}\) and 1000 Nsm\(^{-1}\) respectively. The values of the coefficients were used in previous studies on fast bowling cricket successfully (Felton, 2014). Once the criterion (Section 4.4.1) for ball release was fulfilled, the stiffness and damping parameters were set to zero and the ball released.

### 4.4.1 Position of the ball

In the simulation model, the ball is attached to the hand segment. By considering the ball slipping from the hand to the fingertip at release, the position of the ball in the simulation model was assumed to be at the distal end of the hand segment (Figure 4.3). The distance of the ball from wrist joint was measured to be 20 cm. In order to place the ball in the right position at release relative to the wrist, a correction was made to the wrist angle. This correction ranged from 47° to 57° and was added to the wrist angle (rotation about 1\(^{st}\) axis \((x)\)) depending on the trial used.
Figure 4.3: The pitcher grip a two-seam fastball (left). The contact and release phase (right).

4.4.2 Determination of ball release

Ball release was estimated to occur within the performance data when the horizontal distance between the ball marker and the wrist joint centre had adequately increased (Figure 4.4) to suggest the ball can no longer be in contact with the hand. When calculated in the time interval of 33 ms, all fifteen trials shows that the difference in the horizontal distance between the ball marker and wrist joint centre is greater than 5 cm (Worthington, 2010; Felton, 2014).
Figure 4.4: An example of ball release of Trial 5 with a close-up view; wrist (solid line) and ball horizontal displacement (dotted line). Ball release at time zero.

The ball release velocity (in the horizontal and vertical directions) was calculated over a period of ten frames, starting with the instant of ball release (Worthington, 2010). No forces were considered to act on the ball in the horizontal direction and only gravity was assumed to act in the vertical direction. The ball release velocities were then calculated using equations of constant acceleration.

4.5 Cardan-Euler Angles

Cardan-Euler angles were used to calculate the orientation of one local coordinate system (LCS) with respect to another LCS. The rotation sequence XYZ (Cole et al., 2010).
1993) was chosen which involves three steps: first, rotation about the laterally directed axis (x); second, rotation about the anteriorly directed axis (y); and third, rotation about the vertical axis (z) (Figure 4.5).

Figure 4.5: The Cardan rotation sequence XYZ of rotations first about (a) the x-axis of the stationary coordinate system (α); then about (b) the y'-axis (β); and finally about (c) the z''-axis (γ).

Therefore, the rotation matrix $R$ for an XYZ rotation sequence can be written as

$$R = R_x R_y R_z$$

where

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cosa & sina \\ 0 & -sina & cosa \end{bmatrix}$$

$$R_y = \begin{bmatrix} cosa & 0 & -sina \\ 0 & 1 & 0 \\ sina & 0 & cosa \end{bmatrix}$$

$$R_z = \begin{bmatrix} cosa & sina & 0 \\ -siny & cosy & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In order to construct the rotation matrix, the three matrices (4.3), (4.4) and (4.5) were multiplied which yields
\[
R = \begin{bmatrix}
cos\cos\beta & \cos\sin\beta\sin\alpha + \sin\cos\beta & \sin\sin\alpha - \cos\sin\beta\cos\alpha \\
-\sin\cos\beta & \cos\cos\alpha - \sin\sin\beta\sin\alpha & \sin\sin\beta\cos\alpha + \cos\sin\alpha \\
\sin\beta & -\cos\sin\beta\sin\alpha & \cos\sin\beta\cos\alpha
\end{bmatrix} \tag{4.6}
\]

The matrix, \(R\) describes the relative orientation of an LCS to the global coordinate system (GCS). From the matrix \(R\), the Cardan angle \(\alpha\), \(\beta\) and \(\gamma\) were calculated as follows:

\[
\alpha = \tan^{-1}\left[\frac{-R_{32}}{R_{33}}\right] \tag{4.7}
\]

\[
\beta = \tan^{-1}\left[\frac{R_{31}}{\sqrt{R_{11}^2 + R_{21}^2}}\right] \tag{4.8}
\]

\[
\gamma = \tan^{-1}\left[\frac{-R_{21}}{R_{11}}\right] \tag{4.9}
\]

### 4.5.1 Joint Angular Velocity and Acceleration of Cardan-Euler Joint Angles

The calculation of angular velocity and angular acceleration in a three-dimensional analysis is different compared to a two-dimensional analysis. The derivative of the joint angles (\(\dot{\alpha}, \dot{\beta}, \dot{\gamma}\)) is not equivalent to the joint angular velocity nor is the double derivative equal to angular acceleration because Cardan angles are not vectors (Winter, 2005).

Therefore, the angular velocity of a segment relative to the GCS can be computed by differentiating the rotation matrix using finite differences as follows:

\[
\omega = \frac{d\alpha}{dt} \cdot e_x + \frac{d\beta}{dt} \cdot e_y' + \frac{d\gamma}{dt} \cdot e_z'' \tag{4.10}
\]

where \(e_x, e_y',\) and \(e_z''\) denote the unit vectors of the three rotation axes \(x, y',\) and \(z''\).
Since the first rotation is about $x$-axis and by considering there is no rotation of $\beta$ and $\gamma$, an angular velocity about $x$-axis (1$^{\text{st}}$ rotation) can be written as

$$\omega' = \frac{d\alpha}{dt} \cdot e_x$$  \hspace{1cm} (4.11)

$$\omega' = \begin{bmatrix} \dot{\alpha} \\ 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (4.12)

The second rotation about the $y$-axis will generate angular velocity such as:

$$\omega'' = \frac{d\beta}{dt} \cdot e_y$$  \hspace{1cm} (4.13)

$$\omega'' = \begin{bmatrix} 0 \\ \dot{\beta} \\ 0 \end{bmatrix} + \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \dot{\beta} \\ \sin\beta \dot{\alpha} \end{bmatrix}$$  \hspace{1cm} (4.14)

The angular velocity in third rotation ($z$-axis) can be calculated as:

$$\omega''' = \frac{d\gamma}{dt} \cdot e_z$$  \hspace{1cm} (4.15)

$$\omega''' = \begin{bmatrix} 0 \\ 0 \\ \dot{\gamma} \end{bmatrix} + \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta \dot{\alpha} \\ \dot{\beta} \\ \sin\beta \dot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 \\ \dot{\gamma} \\ \cos\gamma \cos\beta \dot{\alpha} + \sin\gamma \dot{\beta} \end{bmatrix} + \begin{bmatrix} -\sin\gamma \cos\beta \dot{\alpha} + \cos\gamma \dot{\beta} \\ \sin\beta \dot{\alpha} + \dot{\gamma} \end{bmatrix}$$  \hspace{1cm} (4.16)

By decomposing $\omega'''$ into its three components along the three anatomical axes yields

$$\omega = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \cos\beta \cos\gamma & \sin\gamma & 0 \\ -\cos\beta \sin\gamma & \cos\gamma & 0 \\ \sin\beta & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix}$$  \hspace{1cm} (4.17)
As angular velocity is a vector, the angular acceleration can be calculated as the first derivative of angular velocity

\[
\begin{bmatrix}
\alpha_x \\
\alpha_y \\
\alpha_z
\end{bmatrix} = \begin{bmatrix}
\dot{\omega}_x \\
\dot{\omega}_y \\
\dot{\omega}_z
\end{bmatrix}
\]  

(4.18)

### 4.6 Equations of Motion

The Autolev™ software package (Version 3.4) was used to formulate the equations of motion for the angle-driven model and torque-driven models (Chapter 5). Autolev™ have been more commonly used (Allen, 2010; Felton, 2014; King, 1998; Lewis, 2011; Wilson, 2003) due to its ability to generate computer source code, typically Fortran or C, for the mechanical system. This allows the user to incorporate muscle models or an optimisation routine into the basic simulation routine. Other more complex packages limit the access to the source code and prevent the user from customising the model for specific tasks. Autolev™ makes use of Kane’s method to derive the equations of motion. Kane’s method is based on determining partial velocity and partial angular velocity vectors, which are then used to determine generalised active and inertia forces, from which the dynamic equations of motion of the system are defined (Yamaguchi, 2006).

In order for Autolev™ to produce the equations of motion, the user must generate a command file in which:

- The relative positions and orientations of each segment within the system are defined.
- The internal and external forces acting on the system are expressed.

Autolev™ command files were generated in this way for the angle-driven model (Appendix C) and torque-driven model (Appendix B). The simulation model produced by Autolev™ utilises a Kutta-Merson numerical integration algorithm,
which uses a Runge-Kutta integration method to advance the solution of the equations of motion step by step.

4.6.1 Customisation of the Simulation Model

Customisation of the Fortran code produced by Autolev™ was required. Modifications were made to the model to meet specific needs of the study. None of the modifications affected the equations of motion of the system. The customisation of the Fortran code included general alterations and more specific alterations to the simulation model related to the input of initial conditions and other parameter values. These alterations were:

(i) The main segment of the code was converted into a subroutine in order that the whole program could be called from an optimisation program.

(ii) In the angle-driven model, the joint angle time-histories of each of the joints of the body were obtained by calling subroutines which use quintic splines to evaluate the original data.

4.7 Evaluation of the Angle-Driven Model

To ensure that the simulation produced realistic human movements, an evaluation of the angle-driven model was conducted.

4.7.1 Method to Evaluate the Angle-Driven Model

In the model evaluation, ball speed at release produced by the angle-driven model was compared with the ball speed at release from performance data. In addition, the location and velocity of the distal end of each segment were also compared for the angle-driven and performance data. In the experiment, midpelvis was determined as explained in Section 3.5. Right pelvis (or also referred as right hip) was defined as a
midpoint between two markers RASI and RPSI. Left pelvis (or also referred as left hip) was defined as a midpoint between LASI and LPSI. Suprasternal was a midpoint between C7 and clavicle. Right shoulder was a midpoint of three markers named RSHOA, RSHOP and RSHOT. Right elbow was a midpoint between right elbow medial and lateral. Right wrist was a midpoint between wrist medial and lateral.

For the angle-driven simulation model, the length of each segment was measured as part of the anthropometric data collection as described in Section 4.3.1 and the length was assumed to be constant throughout the pitching phase.

4.7.2 Results

Reasonable agreement was found with the difference in average resultant ball release speed between the simulation and the performance is about 0.6 m/s. The average value of resultant ball speed for simulation model is 29 m/s whereas it is 29.6 m/s for performance (Figure 4.6). The ball speed for simulation model lies within 27.9 m/s – 29.8 m/s whereas the ball speed for performance lies within 27.6 m/s – 31.4 m/s.

![Figure 4.6: The resultant speed obtained from the simulation model (solid line) and experiment (dotted line).]
The differences of ball speed in each direction (in m/s) as well as a comparison of resultant speed for each trial were given in Table 4.2. To indicate the goodness of fit between simulation model and performance data, root mean square difference was calculated for the displacement of the distal end of each segment (Tables 4.3 – 4.5). Figures of the displacements and linear velocities of distal segments obtained from the simulation model and performance data of the three trials can be seen in Figure 4.7 – Figure 4.14 (Trial 20) and Appendix F (Trial 10 and Trial 13). These three trials were chosen because the ball speeds at release were among the highest in the fifteen trials. Since the throwing arm for the subject in this study is the right arm, therefore the figures and tables below exclude the left arm.
Table 4.2: Comparison of ball speed at release in each direction and the resultant for each trial (Exp: performance; Sim: angle-driven model)

<table>
<thead>
<tr>
<th>Component</th>
<th>Trial(s)</th>
<th>Ball speed in x-axis (m/s)</th>
<th>Ball speed in y-axis (m/s)</th>
<th>Ball speed in z-axis (m/s)</th>
<th>Resultant speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exp</td>
<td>Sim</td>
<td>Exp</td>
<td>Sim</td>
</tr>
<tr>
<td>Trial 3</td>
<td></td>
<td>-1.44</td>
<td>-1.31</td>
<td>28.71</td>
<td>29.04</td>
</tr>
<tr>
<td>Trial 4</td>
<td></td>
<td>-0.31</td>
<td>-0.39</td>
<td>27.90</td>
<td>29.10</td>
</tr>
<tr>
<td>Trial 5</td>
<td></td>
<td>-0.94</td>
<td>-0.36</td>
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Table 4.5: Root Mean Square Error (in meter) of the displacement of the distal end of each segment for Trial 19, Trial 20, Trial 23, Trial 25 and Trial 26

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**Figure 4.7:** Displacement (left) and linear velocity (right) of midpelvis of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.8: Displacement (left) and linear velocity (right) of right pelvis of Trial 20: simulation model (solid line) and experiment (dotted line).
**Figure 4.9:** Displacement (left) and linear velocity (right) of left pelvis of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.10: Displacement (left) and linear velocity (right) of suprasternal of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.11: Displacement (left) and linear velocity (right) of right shoulder of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.12: Displacement (left) and linear velocity (right) of right elbow of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.13: Displacement (left) and linear velocity (right) of right wrist of Trial 20: simulation model (solid line) and experiment (dotted line).
Figure 4.14: Displacement (left) and linear velocity (right) of the ball of Trial 20: simulation model (solid line) and experiment (dotted line).
4.7.3 Discussion

The average resultant ball speed in this study (29 m/s) is in agreement with the one reported in the previous studies which are between 21.0 m/s and 39.0 m/s (Atwater, 1979; Campbell et al., 2010; Escamilla et al., 2002; Elliot et al., 1988; Feltner and Dapena, 1986; Tarbell, 1971; Werner, 2008). Therefore, this study is fit to give some feedback on technique improvement. It can be seen that there was a difference of about 2-4 cm in the displacement of the distal end of each segment which occurs presumably because the segment length was assumed to be constant throughout the pitching phase in the simulation model.

Dissimilarities in terms of calculation between experiment and angle-driven simulation model might as well contributes to the different about 2-4 cm in the displacement of the distal end of each segment. In the experiment, midpoint between two markers was assumed as the end point/joint. Whilst in simulation, the end point/joint is based on length measured Yeadon’s inertia model.

Additionally, the trunk plus head was assumed to be one rigid segment although in reality the head is one segment and the trunk comprises of two parts; upper and lower trunk. Suprasternal was used to represent as a node for the trunk plus head segment and referred as the upper trunk in the whole thesis. Although this might not be a good representative it has been used in many previous studies (Veeger et al., 1993; Van Der Helm and Pronk, 1995). One segment was used to represent the movement of the shoulder complex. In reality the right shoulder and left shoulder can rotate or elevate about the spine.

In the simulation model, one segment was used to represent the hand segment. Currently, two markers were attached at the medial and lateral aspects of the wrist and one marker was attached at the middle metacarpals. The hand length was measured as explained in section 4.3. For an accurate representation of the hand segment, it is suggested to place more markers at metacarpophalangeal joints and at phalanges of middle finger so that more segments can be added to represent the hand.
and fingers segment. However, the possibilities of marker loss and the camera can’t capture the markers are high.

Also the difference of about 8 cm in the displacement of the ball in z-axis was due to the correction made to the wrist angle (Subsection 4.4.1). However, reasonable agreement was found with the ball release speed between the simulations and the performances (Table 4.2). In addition it can be seen that the Root Mean Square Errors (Table 4.3 – 4.5) of the displacement of the distal end of each segment were relatively small.

4.8 Determination of the Torque-Driven Model Complexity

The angle-driven model together with the joint angles of fifteen trials was used to establish the complexity needed to develop a torque-driven model.

4.8.1 Method to Determine Model Complexity

Before a torque-driven model can be established, two steps to determine the model complexity were carried out. Firstly, the joint angles obtained from the fifteen best trials were examined. The angles from each joint were plotted (Appendix A). The curve of each joint orientation angle was examined in order to determine whether it should be torque-driven or kept as angle-driven. The joint orientation (which will also be referred to as segment orientation/angle throughout the thesis) will be angle-driven if it is almost constant from 0.15 s before ball release. On the other hand, the joint orientation will be torque-driven if the angle shows a substantial gradient prior to ball release. After a thorough observation of the joint angles from fifteen trials, it was decided that the pelvis extension/flexion, pelvis adduction/abduction, upper trunk adduction/abduction, scapula adduction/abduction, right upper arm adduction/abduction, right forearm adduction/abduction, right forearm pronation/supination, right hand extension/flexion, right hand ulnar/radial deviation, left upper arm and left forearm will be kept angle-driven while the pelvis external/internal rotation, upper trunk extension/flexion, upper trunk
external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm external/internal rotation and right forearm flexion/extension will be torque-driven.

The second step was carried out to confirm the decision made in the first step. By allowing one joint angle to be constant, the angle-driven model was used to investigate how this joint angle affects the ball speed at release. The constant value was the value of the angle at ball release. The angle-driven simulation model was used to examine all fifteen trials.

4.8.2 Results

The mean differences of ball speed (in x-, y-, and z-axis) when each orientation was kept constant are presented in Table 4.6 and Table 4.7. A positive value denotes there is an increase in ball speed; whilst a negative value means there is a decrease in ball speed.
Table 4.6: The mean differences of ball speed when each orientation of pelvis, upper trunk and right upper arm were kept constant

<table>
<thead>
<tr>
<th>Joint/Segment orientation</th>
<th>Mean difference in x-axis (m/s)</th>
<th>Mean difference in y-axis (m/s)</th>
<th>Mean difference in z-axis (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis extension/flexion</td>
<td>0.00</td>
<td>1.36</td>
<td>-0.59</td>
</tr>
<tr>
<td>Pelvis adduction/abduction</td>
<td>0.37</td>
<td>-0.07</td>
<td>-0.11</td>
</tr>
<tr>
<td>Pelvis external/internal rotation</td>
<td>-0.26</td>
<td>-1.64</td>
<td>-2.04</td>
</tr>
<tr>
<td>Upper trunk extension/flexion</td>
<td>0.84</td>
<td>-5.24</td>
<td>-0.53</td>
</tr>
<tr>
<td>Upper trunk adduction/abduction</td>
<td>2.06</td>
<td>-0.01</td>
<td>-0.76</td>
</tr>
<tr>
<td>Upper trunk external/internal rotation</td>
<td>0.30</td>
<td>-2.74</td>
<td>-1.63</td>
</tr>
<tr>
<td>Right upper arm flexion/extension</td>
<td>-1.52</td>
<td>3.10</td>
<td>-3.32</td>
</tr>
<tr>
<td>Right upper arm adduction/abduction</td>
<td>1.07</td>
<td>4.75</td>
<td>-2.26</td>
</tr>
<tr>
<td>Right upper arm external/internal rotation</td>
<td>12.13</td>
<td>-9.82</td>
<td>-4.85</td>
</tr>
</tbody>
</table>
Table 4.7: The mean differences of ball speed when each orientation of the right forearm, right hand, scapula, left upper arm and left forearm were kept constant

<table>
<thead>
<tr>
<th>Joint/Segment orientation</th>
<th>Mean difference in $x$-axis (m/s)</th>
<th>Mean difference in $y$-axis (m/s)</th>
<th>Mean difference in $z$-axis (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right forearm extension/flexion</td>
<td>-11.79</td>
<td>-14.86</td>
<td>-1.58</td>
</tr>
<tr>
<td>Right forearm adduction/abduction</td>
<td>0.31</td>
<td>-0.34</td>
<td>-0.19</td>
</tr>
<tr>
<td>Right forearm pronation/supination</td>
<td>-0.03</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Right hand extension/flexion</td>
<td>0.47</td>
<td>-2.08</td>
<td>-4.56</td>
</tr>
<tr>
<td>Right hand ulnar/radial deviation</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Scapula adduction/abduction</td>
<td>-0.31</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>Scapula external/internal rotation</td>
<td>0.21</td>
<td>-1.39</td>
<td>-2.26</td>
</tr>
<tr>
<td>Left upper arm extension/flexion</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Left upper arm adduction/abduction</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Left upper arm external/internal rotation</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Left forearm extension/flexion</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
4.8.3 Discussion

The whole process explained in this section lead to answering research question number one:

1. What complexity of torque-driven simulation model is required to accurately simulate overarm throwing?

The results indicated that most of the joint angles being kept constant resulted in a difference of less than 2.1 m/s in ball speed in x-, y- and z-axis. For that reason, the pelvis extension/flexion, pelvis adduction/abduction, upper trunk adduction/abduction, scapula adduction/abduction, right forearm adduction/abduction, right forearm pronation/supination, right hand ulnar/radial deviation, left upper arm and left forearm will be angle-driven. Although the right hand extension/flexion demonstrates a higher difference in z-axis, observation on the angles from fifteen trials shows that it is almost constant prior to ball release. Therefore, the right hand extension/flexion will be angle-driven. Right upper arm adduction/abduction exhibits a greater difference in each category. Thus, it will be torque-driven. Although scapula external/internal rotations shows a quite small difference in ball speed in each axis, when considering the angles from fifteen trials, it can be seen that prior to ball release the slope of the curve is quite high. Hence, it was decided that the scapula will be torque-driven.

To decide between pelvis and upper trunk, the significance of each segment to ball speed was examined. Previous research shows that the role of pelvis is more to help stabilise the upper body. Although the pelvis external/internal rotation does contribute to ball speed, it occurs between the periods of the beginning of ball deceleration to the start of ball acceleration. Starting from ball acceleration to the start of upper arm internal rotation, upper trunk external/internal rotation is the major contributor to ball speed (Feltner and Nelson, 1996; Stodden et al., 2001; Stodden et al., 2006). Based on this reason, it was decided to keep pelvis external/internal rotation as angle-driven while the upper trunk external/internal rotation is torque-driven.
As a result, the upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm abduction/adduction, right upper arm external/internal rotation and right forearm flexion/extension will be torque-driven.

4.9 Summary

This chapter has described the development and customisation of a 3-dimensional eight-segment angle-driven model. A detailed explanation on the determination of the torque-driven model complexity was also outlined. This led to answering the first research question of this study. The torque-driven model will be established based on the first research question (Chapter 5). The next chapter will explain the parameter determination which will be used within the torque-driven model.
CHAPTER 5
PARAMETER DETERMINATION

5.1 Introduction

Chapter 4 discussed the development of the eight-segment angle-driven model used to simulate overarm throwing. This chapter will discuss the parameters which need to be determined and entered into the torque-driven model in order for the model to be successfully evaluated. The parameters include strength parameters that are required as inputs to the torque-driven simulation model (Chapter 6). The strength parameters are estimated using average values from previous studies (Appendix G) and the net torque at a joint calculated using the angle-driven version of the simulation model with kinematic data from the throwing trials. These parameters specify the relationship between maximum torque and joint angular velocity for a given joint. The subject-specific strength parameters ensure that the model does not produce movements that exceed the strength capabilities of the pitcher.

5.2 Torque-driven Model

In order to understand the technique of overarm throwing, a subject-specific torque-driven simulation model was developed. Torque generators were incorporated at the midpelvis, suprasternal, shoulder and elbow of throwing arm since substantial movement occurred at these joints. At the midpelvis, extensor and flexor torque generators acted to produce upper trunk extension/flexion and upper trunk twist (which will subsequently be referred to as upper trunk external/internal rotation). Pairs of torque generators were incorporated at suprasternal to produce scapula external/internal rotation. At the right shoulder, pairs of torque generators produced upper arm flexion/extension, upper arm adduction/abduction and upper arm
external/external rotation. Pairs of torque generators were also included at the right elbow to produce forearm extension/flexion. These torques applied at each joint centre are the net moments in each direction of all muscular forces acting around the rotation axis of that joint.

The torque-driven model used known initial conditions, and was driven by activation profiles that specified the level of activation of each torque generator. Details of the activation profiles are given in Section 5.3. The recorded performance was specified from 0.29 s before ball release until 0.03 s after ball release. Throughout the simulation the movement of the pitcher was driven by the activation levels of the torque generators. The output of the model included joint angle time histories and ball speed at release.

5.3 Torque Generators

The torque generators expressed maximal voluntary torque as a function of the joint angle and angular velocity.

5.3.1 Activation Profiles

The torque generators used within the torque-driven model represent the maximal voluntary torque that the pitcher can produce. To determine the applied torque this maximal torque was multiplied by a torque activation level:

$$Tq(t) = A(t)T_{q_{\text{max. voluntary}}} \tag{5.1}$$

where $Tq(t)$ is the torque at time $t$, $A(t)$ is the torque activation level at time $t$, and $T_{q_{\text{max. voluntary}}}$ is the maximal voluntary torque. When the torque generator was relaxed, the activation level was 0.0, whereas when the torque generator was fully activated the activation level was 1.0. A quintic function, which has zero velocity
and acceleration at the end points (Yeadon and Hiley, 2000), was used to ramp up or ramp down the activation level using the following equation:

\[
A(t) = a_i + (a_f - a_i) \left( \frac{t - t_i}{t_f - t_i} \right)^3 \left( 6 \left( \frac{t - t_i}{t_f - t_i} \right)^2 - 15 \left( \frac{t - t_i}{t_f - t_i} \right) + 10 \right)
\]  

(5.2)

where \(A(t)\) is the activation level at time \(t\), \(a_i\) is the initial activation level at time \(t_i\) and \(a_f\) is the final activation level at time \(t_f\). This function was chosen as it resulted in a smooth activation profile.

Examples of activation profiles for torque generators during a simulation are given in Figure 5.1 and Figure 5.2. Bold line indicates the activation profile. Table 5.1 lists the seven parameters which were required to define the curves shown in Figure 5.1 and 5.2.

![Activation Profile](image)

**Figure 5.1:** A ramp up and ramp down torque generator activation profile.
Figure 5.2: A ramp down and ramp up torque generator activation profile.

Table 5.1: The seven parameters defining an activation profile

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>Pre-activation level</td>
</tr>
<tr>
<td>$A_1$</td>
<td>Maximum activation level</td>
</tr>
<tr>
<td>$A_2$</td>
<td>Final activation level</td>
</tr>
<tr>
<td>$T_{S1}$</td>
<td>Start time of first ramp</td>
</tr>
<tr>
<td>$T_{R1}$</td>
<td>Ramp time of first ramp</td>
</tr>
<tr>
<td>$T_{P1}$</td>
<td>Time of plateau</td>
</tr>
<tr>
<td>$T_{R2}$</td>
<td>Ramp time of second ramp</td>
</tr>
</tbody>
</table>
5.4 Determination of Joint Torque Parameters

Pitcher strength parameters were initially estimated by taking the average maximum voluntary joint torque measurements obtained from previous studies (Appendix G). In the previous studies, these maximum voluntary data were produced from the processed joint torque measurement data at certain contractile component angles and certain contractile component angular velocities. To express the torque generated as a function of contractile component angle and contractile component angular velocity, such that it could be used within the torque-driven model, a surface (Figure 5.3) was fitted to the joint torque measurement data.

![Figure 5.3: An example of a surface fit to torque data for shoulder flexion (adapted from Jackson, 2010).](image)

Since the torque-driven simulation model in this study used estimated average values from previous studies, the torque was simply expressed as a function of contractile component angular velocity. The torque surfaces were defined based on
the relationships between torque and angular velocity, and differential activation and angular velocity as detailed below.

5.4.1 Fitting a Function to the Data

Two hyperbolic functions representing the concentric phase and the eccentric phase were used to express the maximum torque at full activation as a function of angular velocity (Yeadon et al., 2006). The hyperbolic function representing the concentric phase was a rotational equivalent of the classic Hill hyperbola (1938) and the eccentric phase was representing by an inverted rectangular hyperbola.

5.4.2 Four Parameter Torque / Angular Velocity Function

A rotational equivalent of Hill’s hyperbolic function was used to fit the maximum torque values representing the concentric phase and the eccentric phase was representing by an inverted rectangular hyperbola.

In the concentric phase the relationship between $T$ and $\omega$ is given by the classic Hill hyperbola:

$$(T + T_c)(\omega + \omega_c) = C$$  \hspace{1cm} (5.3)$$

which has asymptotes at $T = -T_c$ and $\omega = -\omega_c$. Rearranging equation (5.3) will produce following:

$$T = \frac{C}{(\omega_c + \omega)} - T_c \hspace{1cm} \text{for } \omega \geq 0$$  \hspace{1cm} (5.4)$$

where

$$T_c = \frac{T_0 \omega_c}{\omega_{max}}$$

$$C = T_c(\omega_{max} + \omega_c)$$

When $\omega = 0$, $T = T_0$: \hspace{1cm} $(T_0 + T_c) \cdot \omega_c = C$
When $\omega = \omega_{max}$, $T = 0$: \hspace{1cm} $T_c(\omega_{max} + \omega_c) = C$
In the eccentric phase, the relationship between torque $T$ and $\omega$ angular velocity was represented by an inverted rectangular hyperbola:

$$(T_e - T)(\omega_e - \omega) = -E \quad ; \text{for } \omega \leq 0 \quad (5.5)$$

which has asymptotes $T = T_e$ and $\omega = \omega_e$. Rearranging equation (5.6) gives:

$$T = \frac{-E}{(\omega_e - \omega)} + T_{max} \quad ; T_{max} = T_e \quad (5.6)$$

where

$$\omega_e = \frac{(T_{max} - T_0)}{kT_0} \cdot \frac{\omega_{max} \cdot \omega_c}{(\omega_{max} + \omega_c)}$$

and $k$ is the ratio of the slopes of the concentric and eccentric phases, which was set at 4.3 which is the theoretical value predicted by Huxley (1957) in his original model.

When $\omega = 0, T = T_0$: \quad $(T_{max} - T_0) \cdot \omega_e = -E$

Three parameters in the concentric phase: $T_0$, the isometric torque value, $\omega_{max}$, the angular velocity value at which the curve reaches zero torque, and $\omega_c$ defined by the vertical asymptote $\omega = -\omega_c$ of the Hill hyperbola, combined together with four parameters in the eccentric phase: $T_{max}$, $T_0$, $\omega_{max}$, and $\omega_c$ yields four parameter function which defined the hyperbolas (Figure 5.4). The value of $T_{max}$ is set to be $1.4T_0$ (Dudley et al., 1990). This four parameter torque / angular velocity function was independent of joint angle.
5.4.3 Seven Parameter Function

In addition to the four parameter torque / angular velocity function, Yeadon et al. (2006) added another three parameter differential activation function to give a seven parameter function. This was done to provide a better fit to the maximum torque values. The activation rises from a plateau $a_{\text{min}}$ in the eccentric region to a maximum $a_{\text{max}}$ in the concentric region. Due to the cumbersome to use the quadratic formula to solve the three parameter differential activation function, Forrester et al., (2011) proposed a less problematic equation (5.7) which has a similar sigmoid function.

$$a = a_{\text{min}} + \frac{(a_{\text{max}}-a_{\text{min}})}{1+\exp\left(\frac{(\omega-\omega_1)}{m}\right)} \quad (5.7)$$

The three parameter differential activation function is presented in Figure 5.5 with $a_{\text{min}}$, the lowest level of activation in the eccentric region, $m$, the effective interval over which the activation increases, which is equal to $10m$ and $\omega_1$, the angular
velocity value at the mid-point of the slope (Figure 5.5). The maximum activation level, $a_{\text{max}}$, was assumed to be equal to 1.

![Differential activation function](image)

**Figure 5.5**: The three parameter differential activation function

### 5.4.4 Torque – Angular Velocity Profiles

Maximum voluntary torque was expressed as the product of the torque / angular velocity and differential activation / angular velocity using the following function:

$$T = T(\omega)a(\omega)$$ \hspace{1cm} (5.8)

In this study, due to the difficulty in experimentally measuring the strength parameters for three-dimensional movement, especially the upper trunk external/internal rotation and scapula external/internal rotation, the torque parameter values for the seven parameters were initially estimated by taking average seven parameter values from previous studies. These initial estimated values are given in Table 5.2, Table 5.3 and Table 5.4.
Table 5.2: Initial estimate of torque – angular velocity profile for upper trunk

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upper trunk extension</th>
<th>Upper trunk flexion</th>
<th>Upper trunk external rotation</th>
<th>Upper trunk internal rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{max}$ (Nm)</td>
<td>523.40</td>
<td>275.20</td>
<td>523.40</td>
<td>275.20</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>373.60</td>
<td>195.60</td>
<td>373.60</td>
<td>195.60</td>
</tr>
<tr>
<td>$\omega_{max}$ (rad/s)</td>
<td>15.50</td>
<td>21.16</td>
<td>15.50</td>
<td>21.16</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>3.82</td>
<td>6.90</td>
<td>3.82</td>
<td>6.90</td>
</tr>
<tr>
<td>$a_{min}$</td>
<td>0.74</td>
<td>0.80</td>
<td>0.74</td>
<td>0.80</td>
</tr>
<tr>
<td>$m$</td>
<td>0.46</td>
<td>1.14</td>
<td>0.46</td>
<td>1.14</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.46</td>
<td>1.43</td>
<td>0.46</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Table 5.3: Initial estimate of torque – angular velocity profile for upper arm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upper arm extension</th>
<th>Upper arm flexion</th>
<th>Upper arm adduction</th>
<th>Upper arm abduction</th>
<th>Upper arm external rotation</th>
<th>Upper arm internal rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{max}$ (Nm)</td>
<td>176.71</td>
<td>123.34</td>
<td>136.48</td>
<td>100.66</td>
<td>47.25</td>
<td>59.73</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>127.76</td>
<td>88.05</td>
<td>97.48</td>
<td>71.90</td>
<td>33.75</td>
<td>42.67</td>
</tr>
<tr>
<td>$\omega_{max}$ (rad/s)</td>
<td>24.42</td>
<td>24.87</td>
<td>18.05</td>
<td>18.00</td>
<td>18.00</td>
<td>19.47</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>8.67</td>
<td>7.19</td>
<td>6.43</td>
<td>6.93</td>
<td>7.20</td>
<td>9.71</td>
</tr>
<tr>
<td>$a_{min}$</td>
<td>0.82</td>
<td>0.78</td>
<td>0.87</td>
<td>0.85</td>
<td>0.90</td>
<td>0.79</td>
</tr>
<tr>
<td>$m$</td>
<td>0.85</td>
<td>0.75</td>
<td>0.06</td>
<td>0.05</td>
<td>1.00</td>
<td>0.17</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.20</td>
<td>-0.64</td>
<td>-0.69</td>
<td>-0.59</td>
<td>0.00</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Table 5.4: Initial estimate of torque – angular velocity profile for scapula and forearm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scapula external rotation</th>
<th>Scapula internal rotation</th>
<th>Forearm extension</th>
<th>Forearm flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$ (Nm)</td>
<td>523.40</td>
<td>275.20</td>
<td>72.73</td>
<td>106.14</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>373.60</td>
<td>195.60</td>
<td>51.95</td>
<td>75.82</td>
</tr>
<tr>
<td>$\omega_{\text{max}}$ (rad/s)</td>
<td>15.50</td>
<td>21.16</td>
<td>18.45</td>
<td>18.10</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>3.82</td>
<td>6.90</td>
<td>5.55</td>
<td>5.43</td>
</tr>
<tr>
<td>$a_{\text{min}}$</td>
<td>0.74</td>
<td>0.80</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td>$m$</td>
<td>0.46</td>
<td>1.14</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.46</td>
<td>1.43</td>
<td>-1.17</td>
<td>-1.53</td>
</tr>
</tbody>
</table>

5.4.5 Optimisation

Simulated Annealing (Corana et al., 1987) was used to minimise the root-mean-square (RMS) difference between the joint angles of the torque-driven model and the angle-driven model to obtain a torque – angular velocity relationship. In this process, $T_0$ was varied and the value of $T_{\text{max}}$ was assumed to be 1.4 times $T_0$ (Dudley et al., 1990; Pain and Forrester, 2009). The lower and upper bounds of $T_0$ were set at ±30% times the initial estimate of $T_0$. These values were chosen because it was sufficient for the Simulated Annealing (Corana et al., 1987) to find a satisfactory value of $T_0$. To determine whether the other six parameters were adequate for a particular movement at a joint, a torque / angular velocity curve was plotted (Figure 5.6). The six parameters were decided to be changed or remained unchanged based on this curve.
Figure 5.6: An example of the seven parameter function fitted for the upper trunk extension torque.

More than one trial was used to obtain a robust set of parameters that may be used for similar movements (Wilson et al., 2006). In this study, three trials have been used to acquire a robust set of parameters. The same process previously described was repeated for the other two trials to obtain an adjusted set of seven parameters which are presented in Table 5.5, Table 5.6 and Table 5.7.
Table 5.5: An adjusted set of torque – angular velocity profile for upper trunk

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upper trunk extension</th>
<th>Upper trunk flexion</th>
<th>Upper trunk external rotation</th>
<th>Upper trunk internal rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$ (Nm)</td>
<td>240.58</td>
<td>428.99</td>
<td>285.57</td>
<td>199.47</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>171.84</td>
<td>306.42</td>
<td>203.98</td>
<td>142.48</td>
</tr>
<tr>
<td>$\omega_{\text{max}}$ (rad/s)</td>
<td>15.50</td>
<td>21.16</td>
<td>15.50</td>
<td>21.16</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>3.82</td>
<td>6.90</td>
<td>3.82</td>
<td>6.90</td>
</tr>
<tr>
<td>$a_{\text{min}}$</td>
<td>0.74</td>
<td>0.80</td>
<td>0.74</td>
<td>0.80</td>
</tr>
<tr>
<td>$m$</td>
<td>0.46</td>
<td>1.14</td>
<td>0.46</td>
<td>1.14</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.46</td>
<td>1.43</td>
<td>0.46</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Table 5.6: An adjusted set of torque – angular profile for upper arm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upper arm extension</th>
<th>Upper arm flexion</th>
<th>Upper arm adduction</th>
<th>Upper arm abduction</th>
<th>Upper arm external rotation</th>
<th>Upper arm internal rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$ (Nm)</td>
<td>150.58</td>
<td>149.63</td>
<td>79.07</td>
<td>81.09</td>
<td>73.35</td>
<td>62.83</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>107.56</td>
<td>106.88</td>
<td>56.48</td>
<td>57.92</td>
<td>52.39</td>
<td>44.88</td>
</tr>
<tr>
<td>$\omega_{\text{max}}$ (rad/s)</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>17.00</td>
<td>15.02</td>
<td>15.02</td>
<td>18.00</td>
<td>15.02</td>
<td>18.00</td>
</tr>
<tr>
<td>$a_{\text{min}}$</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>$m$</td>
<td>1.14</td>
<td>0.90</td>
<td>0.90</td>
<td>1.14</td>
<td>0.90</td>
<td>1.14</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.90</td>
<td>1.43</td>
<td>0.90</td>
<td>1.43</td>
</tr>
</tbody>
</table>
Table 5.7: An adjusted set of torque – angular velocity profile for scapula and forearm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scapula external rotation</th>
<th>Scapula internal rotation</th>
<th>Forearm extension</th>
<th>Forearm flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{max}$ (Nm)</td>
<td>241.92</td>
<td>157.63</td>
<td>114.45</td>
<td>77.38</td>
</tr>
<tr>
<td>$T_0$ (Nm)</td>
<td>172.80</td>
<td>112.59</td>
<td>81.75</td>
<td>55.27</td>
</tr>
<tr>
<td>$\omega_{max}$ (rad/s)</td>
<td>15.50</td>
<td>21.16</td>
<td>40.00</td>
<td>40.00</td>
</tr>
<tr>
<td>$\omega_c$ (rad/s)</td>
<td>3.82</td>
<td>6.90</td>
<td>17.00</td>
<td>15.02</td>
</tr>
<tr>
<td>$a_{min}$</td>
<td>0.74</td>
<td>0.80</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>$m$</td>
<td>0.46</td>
<td>1.14</td>
<td>1.14</td>
<td>0.90</td>
</tr>
<tr>
<td>$\omega_1$ (rad/s)</td>
<td>0.46</td>
<td>1.43</td>
<td>1.43</td>
<td>0.90</td>
</tr>
</tbody>
</table>

5.5 Discussion

Due to the difficulty in experimentally measuring the strength parameters for three-dimensional movements (especially the upper trunk external/internal rotation and scapula external/internal rotation), the torque parameter values for the seven parameters were initially estimated by taking average parameter values from previous studies (Appendix G). By varying $T_0$ and the activation parameters in matching simulations, a new set of maximum voluntary joint torques were obtained. Calculating the seven parameters value using this process is appropriate but time consuming because the process requires repetitions to obtain a suitable set of values which are able to represent the pitcher strength. The torque-profile for each actuator was solely constructed on the torque-angular velocity relationship and not a joint angle dependent which mean it does not account the muscle-tendon complex. However in this study, the root-mean-square (RMS) difference between the joint angles and the ball speed at release of the torque-driven model and the angle-driven
model gives a close match indicates that it is adequate to construct the torque-profile solely on the torque-angular velocity relationship. In future it will be ideal if the torque-angle and torque-angular velocity relationships are incorporated in the model so that its effect on the performance of the pitcher can be observed.

5.6 Conclusion

The strength of the pitcher at a joint was initially determined from previous studies and subsequently adjusted by varying the value of $T_0$. The next chapter will describe the model evaluation of the torque-driven model.
CHAPTER 6
MODEL EVALUATION

6.1 Introduction

To confidently use the torque-driven simulation model for further analyses, an evaluation of the model is required. This chapter describes the evaluation of the torque-driven simulation model based on comparisons between simulation and performance. Simulated Annealing was used to vary the parameters for the model evaluation and optimisation.

6.2 Model Evaluation

The torque-driven simulation model has a pair of torque generators for each joint angle which add up to a total of fourteen torque generators. The maximum voluntary torque values for a particular joint angle and joint angular velocity were initially estimated by taking average voluntary torque values from previous studies. The value of $T_0$ for each torque generator was varied to give a new set of maximum voluntary torques which appropriately represents pitcher strength. At first, upper trunk extension/flexion was torque-driven and matched while other joints were kept angle-driven. For each torque generator, eight parameters were varied using Simulated Annealing (Corana et al., 1987). The eight parameters were $T_0$ and seven activation parameters (Section 5.3.1). The inputs for the model comprised of the joint angle time histories and the joint angular velocities gained from angle-driven model, the spring coefficients and the body segmental inertias. The model parameters were varied until a good match between the torque-driven model and the angle-driven model was found. The optimised $T_0$ values for upper trunk extension/flexion obtained in the first part of the matching process were used in the
second re-optimisation. Subsequently, upper trunk extension/flexion and upper trunk external/internal rotation were torque-driven while other joints were kept angle-driven. The same process was repeated to get the optimise value of $T_0$ for the upper trunk extension/flexion and upper trunk external/internal rotation. These processes were repeated until all fourteen torque generators were included in the model. As the model used the average voluntary torque values from previous studies, step-by-step re-optimisation needs to be done in order to get the best $T_0$ values that represents the strength of the pitcher in this study. In order to examine the robustness, these optimised $T_0$ values were used to evaluate the other trials to get a new set of $T_0$ as presented in Section 5.4.5.

### 6.3 Objective Function

To assess how well the simulations matched the performances each simulation was given a score:

- Root mean square (RMS) differences in the joint angles (which will also be referred to as segment name throughout the thesis): upper trunk extension/flexion ($\theta_1$), upper trunk external/internal rotation ($\theta_2$), scapula external/internal rotation ($\theta_3$), right upper arm flexion/extension ($\theta_4$), right upper arm adduction/abduction ($\theta_5$) and right upper arm external/internal rotation ($\theta_6$).

- The difference in ball velocity vector at ball release (calculated in $x$-direction, $y$-direction and $z$-direction) expressed as a percentage of the relative ball velocity.

The score function was calculated by taking the overall RMS of these components which reduced the chances of any one of the components being neglected during the optimisation process. The overall score of the simulation was calculated as follows:

$$\text{Total Score} = \sqrt{\frac{v^2 + \theta_1^2 + \theta_2^2 + \theta_3^2 + \theta_4^2 + \theta_5^2 + \theta_6^2}{7}}$$  \quad (6.1)
The joint angle difference and ball speed were equally weighted, where 1\(^\circ\), was considered comparable to a 1\% difference in other measures (Yeadon and King, 2002).

### 6.4 Matching Optimisations

Flexor and extensor torque activation profiles were used to represent upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper arm external/internal rotation. Table 6.1 lists the corresponding torque activation profile for the particular movement.

**Table 6.1: Joint/Segment movements and corresponding torque activation profiles**

<table>
<thead>
<tr>
<th>Joint/Segment Movement</th>
<th>Activation Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trunk extension</td>
<td>Extensor</td>
</tr>
<tr>
<td>Upper trunk flexion</td>
<td>Flexor</td>
</tr>
<tr>
<td>Upper trunk external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Upper trunk internal rotation</td>
<td>Flexor</td>
</tr>
<tr>
<td>Scapula external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Scapula internal rotation</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm flexion</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm extension</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm adduction</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm abduction</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm internal rotation</td>
<td>Flexor</td>
</tr>
</tbody>
</table>
6.4.1 Results

Overall reasonable matches were found when the upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper arm external/internal rotation were torque-driven (Table 6.2; Figure 6.1). Figure 6.1 shows that the model was tending to move in the same way as the performance data at all joints, although the matches for right upper arm flexion/extension and right upper arm adduction/abduction had larger errors. The differences for adduction/abduction occur around 150 ms before ball release whereas for flexion/extension the differences are in the last 100 ms before ball release.
Table 6.2: RMS differences between performances and matched simulation from three trials

<table>
<thead>
<tr>
<th>Trials / Output</th>
<th>Trial 20</th>
<th>Trial 16</th>
<th>Trial 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint/Segment angle (in °)</td>
<td>15.40</td>
<td>15.90</td>
<td>15.35</td>
</tr>
<tr>
<td>Upper trunk extension/flexion</td>
<td>0.98</td>
<td>1.56</td>
<td>1.61</td>
</tr>
<tr>
<td>Upper trunk external/internal rotation</td>
<td>5.50</td>
<td>6.35</td>
<td>7.24</td>
</tr>
<tr>
<td>Scapula external/internal rotation</td>
<td>2.10</td>
<td>3.09</td>
<td>4.04</td>
</tr>
<tr>
<td>Right upper arm flexion/extension</td>
<td>26.10</td>
<td>25.89</td>
<td>25.72</td>
</tr>
<tr>
<td>Right upper arm adduction/abduction</td>
<td>25.80</td>
<td>26.83</td>
<td>25.51</td>
</tr>
<tr>
<td>Right upper arm external/internal rotation</td>
<td>6.80</td>
<td>8.61</td>
<td>7.16</td>
</tr>
<tr>
<td>Ball speed (in %)</td>
<td>6.0</td>
<td>4.6</td>
<td>5.5</td>
</tr>
<tr>
<td>x-direction</td>
<td>0.34</td>
<td>-0.22</td>
<td>1.30</td>
</tr>
<tr>
<td>y-direction</td>
<td>-0.61</td>
<td>-0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>z-direction</td>
<td>-0.86</td>
<td>-0.88</td>
<td>0.09</td>
</tr>
<tr>
<td>Total score (in %)</td>
<td>13.0</td>
<td>13.8</td>
<td>13.4</td>
</tr>
</tbody>
</table>
The activation profile and joint torque time histories for each individual angle are presented in Figure 6.2, Figure 6.3 and Figure 6.4. Ball release is at time zero.

**Figure 6.1**: Joint angles time-histories for a matched simulation of Trial 20 (torque-driven: solid line, angle-driven: dashed line).
Figure 6.2: Activation profiles for the individual angles of Trial 20.
Figure 6.3: Activation profiles for the individual angles of Trial 20.
6.4.2 Matching Optimisations including Elbow

The same process as explained previously was repeated by including a pair of torque generators at the elbow for the forearm extension/flexion ($\theta_T$). Table 6.3 lists the corresponding torque activation profile for the particular movement.
Table 6.3: Joint/Segment movements and corresponding torque activation profiles

<table>
<thead>
<tr>
<th>Joint/Segment Movement</th>
<th>Activation Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trunk extension</td>
<td>Extensor</td>
</tr>
<tr>
<td>Upper trunk flexion</td>
<td>Flexor</td>
</tr>
<tr>
<td>Upper trunk external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Upper trunk internal rotation</td>
<td>Flexor</td>
</tr>
<tr>
<td>Scapula external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Scapula internal rotation</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm flexion</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm extension</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm adduction</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm abduction</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right upper arm external rotation</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right upper arm internal rotation</td>
<td>Flexor</td>
</tr>
<tr>
<td>Right forearm flexion</td>
<td>Extensor</td>
</tr>
<tr>
<td>Right forearm extension</td>
<td>Flexor</td>
</tr>
</tbody>
</table>

$T_0$ and seven parameters of activation profile were varied to obtain a reasonable agreement between performance and matching simulation. The overall score of the simulation was recalculated as follows:
Total Score = \sqrt{\left(\frac{v^2 + \theta_1^2 + \theta_2^2 + \theta_3^2 + \theta_4^2 + \theta_5^2 + \theta_6^2 + \theta_7^2}{8}\right)} \quad (6.2)

6.4.3 Penalties

Where necessary, the optimisation incurred penalties if the joint angles went beyond the pitcher’s anatomical limits. A penalty equivalent to 1% was incurred for each degree that the joint angle exceeded the limits given in Table 6.4. None of the penalties incurred in the optimisations.

Table 6.4: Limits of range-of-motion of the joints/segments (measured in °)

<table>
<thead>
<tr>
<th>Joint/Segment</th>
<th>Lower angle limit (°)</th>
<th>Upper angle limit (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trunk extension</td>
<td>-45°</td>
<td>45°</td>
</tr>
<tr>
<td>Upper trunk external/internal rotation</td>
<td>-45°</td>
<td>45°</td>
</tr>
<tr>
<td>Scapula external/internal rotation</td>
<td>-45°</td>
<td>45°</td>
</tr>
<tr>
<td>Right upper arm flexion/extension</td>
<td>-180°</td>
<td>90°</td>
</tr>
<tr>
<td>Right upper arm abduction/adduction</td>
<td>-180°</td>
<td>10°</td>
</tr>
<tr>
<td>Right upper arm external/internal rotation</td>
<td>-350°</td>
<td>0°</td>
</tr>
<tr>
<td>Right forearm flexion/extension</td>
<td>-10°</td>
<td>180°</td>
</tr>
</tbody>
</table>

6.4.4 Matching Optimisations including Elbow Results

However, no satisfactory results were achieved when the elbow torque-driven with the overall score increased from 13.0% to 30.0% as presented in Table 6.5.
Table 6.5: RMS differences between model with elbow angle-driven and model with elbow torque-driven

<table>
<thead>
<tr>
<th>Output</th>
<th>Elbow angle-driven</th>
<th>Elbow torque-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint/Segment angle (in °)</td>
<td>15.4</td>
<td>43.6</td>
</tr>
<tr>
<td>Upper trunk extension/flexion</td>
<td>0.98</td>
<td>26.09</td>
</tr>
<tr>
<td>Upper trunk external/internal rotation</td>
<td>5.50</td>
<td>13.85</td>
</tr>
<tr>
<td>Scapula external/internal rotation</td>
<td>2.10</td>
<td>10.87</td>
</tr>
<tr>
<td>Right upper arm flexion/extension</td>
<td>26.10</td>
<td>55.67</td>
</tr>
<tr>
<td>Right upper arm adduction/abduction</td>
<td>25.80</td>
<td>58.55</td>
</tr>
<tr>
<td>Right upper arm external/internal rotation</td>
<td>6.80</td>
<td>56.05</td>
</tr>
<tr>
<td>Right forearm extension/flexion</td>
<td>-</td>
<td>50.18</td>
</tr>
<tr>
<td>Ball speed (in %)</td>
<td>6.0</td>
<td>4.2</td>
</tr>
<tr>
<td>x-direction</td>
<td>0.34</td>
<td>1.10</td>
</tr>
<tr>
<td>y-direction</td>
<td>-0.61</td>
<td>-0.08</td>
</tr>
<tr>
<td>z-direction</td>
<td>-0.86</td>
<td>-0.05</td>
</tr>
<tr>
<td>Total score (in %)</td>
<td>13.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>
In this matching simulation, although the ball speed gives a good match; the joint angles give a poor match. To overcome this matter, the activation profiles were adjusted by adding another three parameters to the existing activation profile, giving ten parameters for the right forearm extensor/flexor activation profile. For the other joints, the activation profiles remained at seven parameters since the torque generators were able to produce sensible results. Table 6.6 listed the ten parameters required to define the curves as shown in Figure 6.5 and Figure 6.6. To gain a good agreement between performance and matching simulation, the process was repeated by varying $T_0$ and ten parameters of activation profile.

**Table 6.6: Ten parameters defining activation profile**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>Pre-activation level</td>
</tr>
<tr>
<td>$A_1$</td>
<td>Second activation level</td>
</tr>
<tr>
<td>$A_2$</td>
<td>Maximum activation level</td>
</tr>
<tr>
<td>$A_3$</td>
<td>Final activation level</td>
</tr>
<tr>
<td>$T_{S1}$</td>
<td>Start time of first ramp</td>
</tr>
<tr>
<td>$T_{R1}$</td>
<td>Ramp time of first ramp</td>
</tr>
<tr>
<td>$T_{P1}$</td>
<td>Time of first plateau</td>
</tr>
<tr>
<td>$T_{R2}$</td>
<td>Ramp time of second ramp</td>
</tr>
<tr>
<td>$T_{P2}$</td>
<td>Time of second plateau</td>
</tr>
<tr>
<td>$T_{R3}$</td>
<td>Ramp time of third ramp</td>
</tr>
</tbody>
</table>
Figure 6.5: A torque generator activation profile: ramp up, ramp up and ramp down.

Figure 6.6: A torque generator activation profile: ramp down, ramp down and ramp up.
With the adjusted activation profile, the total score decreased from 30.0% to 26.0% (Table 6.7). Although it gives a slightly better match, the joint angles comparison is still poor. On the other hand, the ball speed at release gives a good match between performance and matching simulation.

Table 6.7: RMS differences between model with seven-parameter and model with ten-parameter activation profile

<table>
<thead>
<tr>
<th>Output</th>
<th>Model with seven-parameter</th>
<th>Model with ten-parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint/Segment angle (in °)</td>
<td>43.6</td>
<td>34.3</td>
</tr>
<tr>
<td>Upper trunk extension/flexion</td>
<td>26.09</td>
<td>17.30</td>
</tr>
<tr>
<td>Upper trunk external/internal rotation</td>
<td>13.85</td>
<td>10.85</td>
</tr>
<tr>
<td>Scapula external/internal rotation</td>
<td>10.87</td>
<td>7.87</td>
</tr>
<tr>
<td>Right upper arm flexion/extension</td>
<td>55.67</td>
<td>43.43</td>
</tr>
<tr>
<td>Right upper arm adduction/abduction</td>
<td>58.55</td>
<td>47.89</td>
</tr>
<tr>
<td>Right upper arm external/internal rotation</td>
<td>56.05</td>
<td>44.17</td>
</tr>
<tr>
<td>Right forearm extension/flexion</td>
<td>50.18</td>
<td>39.03</td>
</tr>
<tr>
<td>Ball speed (in %)</td>
<td>4.2</td>
<td>5.6</td>
</tr>
<tr>
<td>x-direction</td>
<td>1.10</td>
<td>-0.71</td>
</tr>
<tr>
<td>y-direction</td>
<td>-0.08</td>
<td>-0.45</td>
</tr>
<tr>
<td>z-direction</td>
<td>-0.05</td>
<td>-0.47</td>
</tr>
<tr>
<td>Total score (in %)</td>
<td>30.0</td>
<td>26.0</td>
</tr>
</tbody>
</table>
6.5 Discussion

It is not clear why the right forearm does not match when the forearm extension/flexion angle was torque driven. It could be due to interactions from proximal segments mainly by the upper trunk external/internal rotation, scapula external/external rotation and right upper arm external/inter rotation or perhaps right forearm adduction/abduction and right forearm pronation/supination needs to be included in the model. Due to this issue, a further investigation is required to observe what factors prevent the right forearm from behaving sensibly.

The poor match for the upper arm abduction/adduction mostly occurs from 0.3s to 0.1s before ball release. Whilst for the upper arm flexion/extension, large errors occurred 0.1s prior to ball release. Although equal weightage was given to the overall score to prevent any components being neglected during optimisation process, seemingly some joints angle such as upper arm flexion/extension and upper arm abduction/adduction were sacrificed to allow a good positioning of the ball to achieve high speed at release. Yet, the optimisations always produced a good match for ball speed at release for both model with right forearm angle-driven or model with right forearm torque-driven,

Previous studies identified that the right forearm extensors (the triceps) can’t shorten fast enough to generate the high angular velocity measured at the elbow (Fleisig and Escamilla, 1996; Werner et al., 1993). The high angular velocity of the elbow prior to ball release was primarily powered by segments proximal to the elbow, particularly the rotation of the upper arm, trunk and pelvis (Feltner and Dapena, 1986; Fleisig and Escamilla, 1996; Roach et al., 2013; Werner et al., 1993). Dobbins (reported by Roberts, 1971) used a differential nerve block to paralyse triceps activity. After six practice trials, the subject was able to throw the ball at over 80% of the speed attained prior to the paralysation of the triceps. In a study by Feltner and Dapena (1986), the value of the forearm extension torque is quite small, and they strongly suggests that the extension of the forearm at elbow is not due primarily to the action of the triceps but to the resultant joint force exerted by the upper arm on the forearm at the elbow. Their study indicated that a force pointing from the
elbow joint towards the shoulder joint would lead to the extension of the forearm. Such a force could be associated with a centripetal acceleration of the elbow joint as the upper arm performs its abduction and extension rotations about the shoulder joint, or it could be produced by a linear acceleration of the trunk twist.

Ahn (1991) used computer simulations and optimisation techniques in comparing theoretical data with experimental data. His data showed that hand velocity at ball release was approximately 80% of the experimental result when the resultant elbow joint torque was set to zero, approximately 95% of the experimental value when resultant wrist joint torque was set to zero, and approximately 75% of the experimental value when both the resultant elbow and wrist joint torques were set to zero. Consequently, he concluded that ball velocity at release was generated primarily by body segments proximal to the forearm.

Apparently, the forearm extension prior to ball release is mainly resulted from the action of centripetal force and barely of the action of triceps. As the throwing exploit the whip characteristics of the extremities, the ball speed at release is presumably not due to the transfer of momentum from the forearm to the hand and finally to the ball, but due to the rotation of the pelvis, upper trunk and upper arm.

Therefore, the right forearm extension/flexion was kept angle-driven. The model remained with torque generators included at the upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper arm external/internal rotation.

Figure 6.1 shows that the model with the forearm extension/flexion angle driven was tending to move in the same way as the performance data at all joints, although the matches for right upper arm flexion/extension and right upper arm adduction/abduction had larger errors (Table 6.2). The differences for adduction/abduction occur around 150 ms before ball release whereas for flexion/extension the differences are in the last 100 ms before ball release (Figure 6.1). It is not clear why these two angles were not matched as well as other joints,
but the overall difference score was reasonable and deemed sufficient to use the model for subsequent optimisations with the limitations of having the forearm extension/flexion angle driven.

### 6.6 Summary

This chapter has described the method of evaluation of the torque-driven model. The torque-driven model with the elbow/forearm kept angle-driven was able to replicate key performance features of overarm throwing, with a mean overall difference of 13%. The simulation model is thus considered suitable to investigate and optimise performance in overarm throwing.
CHAPTER 7

MODEL APPLICATION AND PERFORMANCE ANALYSIS

7.1 Introduction

The motivation for the present study was to analyse overarm throwing to gain an understanding of the mechanics of fastball pitching, and then to utilise this understanding to identify ways to improve performance. This chapter will describe the methods used to apply the simulation model of overarm throwing to answer specific research questions.

7.2 Technique Optimisation

An optimal performance of overarm throwing in fastball pitching is one in which the pitcher performs a throw with a high ball velocity at release whilst trying to prevent the batter from hitting the ball. A simulation model allows an investigation into the technique of the fastball pitcher used within this research and examine whether the technique used by the pitcher is close to optimum.

7.2.1 Technique Optimisation Method

To answer this research question, Simulated Annealing (Corana et al., 1987) was used to maximise the resultant ball velocity at release. 128 parameters were varied which comprised the activation parameters for each joint rotation. During the simulation, penalties were included in the score function to prevent the joint angles from exceeding the limit. If the range was exceeded, a penalty equivalent to 1
percentage point was incurred for each degree that the joint angle exceeded the limits (Section 6.4.3). None of the penalties incurred in the optimum solution.

### 7.2.2 Technique Optimisation Results

The joint angle time-histories (Figure 7.1), joint activation level (Figure 7.2; Figure 7.3) and joint torque time-histories (Figure 7.4) were compared for the optimal technique and matching simulation. The resultant ball speed increased by 14.09% from 29.1 m/s to 33.2 m/s at release. In the optimised technique, the upper trunk flexion and the right scapula internal rotation are higher at ball release. Prior to ball release, the right upper arm flexion and the right upper arm external rotation are higher in the optimised technique compared to the matching simulation. The upper trunk external/internal rotation and the right upper arm abduction/adduction are almost the same throughout the movement compared to matching simulation with the right upper arm adducted more at ball release.

Observing the angular velocity time-histories in Figure 7.5, the upper trunk extension reaches high angular velocity first followed by upper trunk internal rotation. Subsequently, after the scapula reaches high angular velocity, the upper arm extension, upper arm abduction and upper arm internal rotation reach high angular velocity at the same time at ball release. It can be said that for throwing at maximum speed, the proximal-to-distal sequencing occurs from upper trunk to scapula and finally to the upper arm.
Figure 7.1: Comparison of the joint angle time-histories for optimal technique (solid line) and matching simulation (dashed line) of Trial 20.
Figure 7.2: Comparison of the joint activation level for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20.
Figure 7.3: Comparison of the joint activation level for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20.
Figure 7.4: Comparison of the joint torque time-histories for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20.
**Figure 7.5**: Comparison of the joint angular velocity time-histories for the optimal technique (solid line) and matching simulation (dashed line) of Trial 20.
7.2.3 Discussion

The simulation model was applied to investigate optimal technique in overarm throwing. This lead to answering the second research question:

1. How close to optimal is the technique of the fastball pitcher in this study?

The results indicated that the pitcher could increase performance by around 14%. There are several factors that influence this optimal result. Greater upper arm external rotation prior to ball release shown in the optimised technique is one of the factors contributes to the ball speed which agreed with the result found by previous studies (Matsuo et al., 2001; Escamilla et al., 2002). During this time, high angular velocity of upper arm internal rotation was generated which then transferred to the ball at release (Seroyer et al., 2010). The greater upper arm flexion observed in the optimised technique resulted in a greater range of distance of the ball to travel before release which agreed with the result found by Escamilla et al. (2002).

Additionally, upper trunk flexion and the scapula internal rotation are higher at ball release in the optimised technique. These findings are in agreement with previous studies that indicated that greater forward flexion and upper trunk twist at ball release helped in transferring the angular momentum from lower extremity to the ball at release (Feltner and Nelson, 1996; Matsuo et al., 2001; Stodden et al., 2001; 2006). The upper trunk external/internal rotation is almost the same throughout the movement compared to the matching simulation. However, scapula internal rotation is higher at ball release. This result indicated that instead of upper trunk twist, actually the scapula internal rotation is the contributor to the ball speed at release. In overarm throwing, the scapula can be thought of as a funnel through which the generated forces are passed to the upper extremity. If there is turbulence in the funnel, the efficiency of the transmission of the generated forces is diminished. Therefore, the position and the motion of the scapula are crucial during all the phases of the overarm throwing motion. Proper cocking in the externally rotated position and proper follow-through allows consistent glenohumeral joint function (Kibler, 1991). Although the internal rotation of the upper trunk is the same
throughout the movement compared to the matching simulation, the combination between the upper trunk internal rotation and the scapula internal rotation allowed a more forward position (Veeger et al., 1993) for the upper extremity to propel the ball. Although the scapula movement relative to the trunk was moderate, it affected the muscle orientations significantly (Lin et al., 2005). The most significant effect of scapula movement on the muscle moment arm were found in the middle and posterior deltoid, biceps long head, teres major, teres minor, supraspinatus and the infraspinatus muscles (Lin et al., 2005).

Additionally, through the optimised technique, the proximal-to-distal sequencing can be observed via the angular velocity of each joint orientation.

### 7.3 Strength Optimisation

An understanding of the kinematics and kinetics of pitching can assist in technique and strength-training programs that focus on performance enhancement and injury prevention. Using the computer simulation model of overarm, the effects of increasing the joint strength will be investigated and thus, answering the third research question:

3. How does a 5% increase in strength affect ball release speed?

#### 7.3.1 Strength Optimisation Method

Simulated Annealing (Corana et al., 1987) was used to vary seven activation parameters per torque generator to maximise an objective function which comprised solely of the ball speed. During the optimisation the joint angle constraints outlined in Section 6.4.3 were employed to ensure that the joint angles did not exceed the anatomical bounds of the pitcher. A penalty equivalent to 1% was incurred for each degree that the joint angle exceeded the limits. None of the penalties incurred in the optimisations. The $T_0$ values for all torque generators were increased by 5%. An
optimisation was carried out to determine the effect of increasing 5% strength on the performance of the pitcher.

7.3.2 Strength Optimisation Results

The joint angle time-histories, activation profiles and joint torque time-histories are presented in Figure 7.6, Figure 7.7, Figure 7.8 and Figure 7.9, respectively. The resultant ball velocity increased by 0.6% from 33.2 m/s to 33.4 m/s. The upper trunk extension/flexion, upper trunk external/internal rotation and right upper arm external/internal rotation show similar patterns when compared with the actual strength (optimisation of technique simulation). The scapula external/internal rotation, right upper arm flexion/extension and right upper arm abduction/adduction show a different trend prior to ball release when the strength was increased by 5%. However apart from right upper arm adduction/abduction, all joint angles are similar at ball release when compared to the actual strength optimal simulation.
Figure 7.6: Comparison of the joint angle time-histories for optimal technique for actual strength (dashed line) and increased strength (solid line) of Trial 20.
Figure 7.7: Comparison of the torque generator activation level for actual strength (dashed line) and increased strength (solid line) of Trial 20.
Figure 7.8: Comparison of the torque generator activation level for actual strength (dashed line) and increased strength (solid line) of Trial 20.
**Figure 7.9:** Comparison of the joint torque time-histories for actual strength (dashed line) and increased strength (solid line) of Trial 20.

### 7.3.3 Discussion

The net moment calculated as the total rotational force acting on a joint is responsible for the limb motion around the joint axis. The net moment consists of the sum of the muscular moments (interactions of muscular moments), motion-
dependent moments, and gravitational moments (Schneider et al., 1989). Motion-dependent moments are reactive (i.e., a segment's reactions to the movements of mechanically linked segments) and composed of either inertial forces proportional to segmental accelerations or centripetal forces proportional to the square of segmental velocities. On the other hand, muscular moments are active occurring from muscle contractions and passive deformations of muscle and other soft tissue crossing the joint. Gravitational moments are moments resulting from gravity, acting at the centre-of-mass of each segment (Heise and Cornwell, 1997; Putnam, 1991).

The $T_o$ value in this study refers to the muscular moment acting on each joint relative to each joint axis. Since it is not known which segment strength is significant to produce a higher ball speed at release, $T_o$ value for all segments relative to each joint axis were increased by 5%. As a result, an increase of 0.6% in ball speed at release was observed if the strength of each joint was increased by 5%. The small increment in ball speed is presumably due to the compensation between segments interaction which are linked together in the system. In multi-joint movements, a joint is rotated not only by the muscle and gravity torques but also by the interaction torque that arises from motions of the linked limb segments. A greater torque value in all joints apparently not helped in producing a greater ball speed at release. Seemingly a greater torque value in one joint orientation will affect another joint orientation which causes the joint orientation to compensate in order to produce a higher ball speed at release. Thus, this result lead to the next research question to observe which torque generators could benefit if the increased strength ($T_o$) were varied by ±30%.

### 7.4 Varying the Strength Optimisation

The ball resultant velocity at release shows a slight increase when the strength was increased by 5%. An optimisation was carried out to observe which torque generators could benefit from a greater than 5% increase in strength and thus, answering the fourth research question.
4. *How does a ±30% change in strength affect ball release speed?*

### 7.4.1 Varying the Strength Optimisation Method

Simulated Annealing (Corana et al., 1987) was used to vary all $T_o$ values by ±30% along with the seven activation parameters per torque generator. During the optimisation the joint angle constraints outlined in Section 6.4.3 were employed to ensure that the joint angles did not exceed the anatomical bounds of the pitcher. A penalty equivalent to 1% was incurred for each degree that the joint angle exceeded the limits. None of the penalties incurred in the optimisations.

### 7.4.2 Varying the Strength Optimisation Results

The joint angle time-histories, activation profiles and joint torque time-histories are presented in Figure 7.10, Figure 7.11, Figure 7.12 and Figure 7.13, respectively. The resultant ball velocity increased by 2.7% from 33.4 m/s to 34.3 m/s. The scapula internal rotation, right upper arm abduction and right upper arm extension are slightly higher at ball release. The upper trunk external/internal rotation and right upper arm external/internal rotation shows different pattern prior to ball release, however the angles are similar at ball release. The upper trunk extension/flexion shows a slight decrease throughout the movement. At the late arm cocking (about 50 ms prior to ball release), although right upper arm external rotation is somewhat less (about 30°), the right upper arm flexion and right upper arm abduction are higher which permitted a higher ball speed at release.
Figure 7.10: Comparison of the joint angle time-histories for optimal technique for increased strength (dashed line) and varied increased strength (solid line) of Trial 20.
Figure 7.11: Comparison of the torque generator activation level for increased strength (dashed line) and varied increased strength (solid line) of Trial 20.
Figure 7.12: Comparison of the torque generator activation level for increased strength (dashed line) and varied increased strength (solid line) of Trial 20.
Figure 7.13: Comparison of the joint torque time-histories for increased strength (dashed line) and varied increased strength (solid line) of Trial 20.

Referring to Table 7.1, it can be seen that the $T_o$ values for upper trunk extension and flexion, scapula external rotation, right upper arm flexion, right upper arm adduction and right upper arm external rotation increased by more than 5%. In contrast, the $T_o$ values for upper trunk internal rotation, scapula internal rotation,
upper arm internal rotation, right upper arm extension and right upper arm abduction dropped more than 5%. The $T_o$ values for upper trunk external rotation and right upper arm internal rotation demonstrated a small decreased.

Table 7.1: Comparison of the $T_o$ values

<table>
<thead>
<tr>
<th>Joint/Segment angles</th>
<th>Matching Optimisation</th>
<th>Technique Optimisation</th>
<th>5% Increase Strength Optimisation</th>
<th>±30% Strength Optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trunk extension</td>
<td>172</td>
<td>172</td>
<td>180</td>
<td>183</td>
</tr>
<tr>
<td>Upper trunk flexion</td>
<td>306</td>
<td>306</td>
<td>322</td>
<td>353</td>
</tr>
<tr>
<td>Upper trunk external rotation</td>
<td>204</td>
<td>204</td>
<td>214</td>
<td>206</td>
</tr>
<tr>
<td>Upper trunk internal rotation</td>
<td>142</td>
<td>142</td>
<td>150</td>
<td>117</td>
</tr>
<tr>
<td>Scapula external rotation</td>
<td>173</td>
<td>173</td>
<td>181</td>
<td>186</td>
</tr>
<tr>
<td>Scapula internal rotation</td>
<td>113</td>
<td>113</td>
<td>118</td>
<td>85</td>
</tr>
<tr>
<td>Right upper arm flexion</td>
<td>107</td>
<td>107</td>
<td>112</td>
<td>134</td>
</tr>
<tr>
<td>Right upper arm extension</td>
<td>108</td>
<td>108</td>
<td>113</td>
<td>95</td>
</tr>
<tr>
<td>Right upper arm adduction</td>
<td>56</td>
<td>56</td>
<td>59</td>
<td>66</td>
</tr>
<tr>
<td>Right upper arm abduction</td>
<td>58</td>
<td>58</td>
<td>61</td>
<td>47</td>
</tr>
<tr>
<td>Right upper arm external rotation</td>
<td>52</td>
<td>52</td>
<td>55</td>
<td>67</td>
</tr>
<tr>
<td>Right upper arm internal rotation</td>
<td>45</td>
<td>45</td>
<td>47</td>
<td>46</td>
</tr>
</tbody>
</table>
7.4.3 Discussion

As the segments are linked in the kinetic chain, increasing the strength of one rotation will affect another due to the interactions between segments. Although not all torque generators could benefit from a greater than 5% increase in strength, but decreasing in certain torque generators is necessary in order to produce a higher ball speed at release. Therefore, by varying the increased $T_o$ by ±30%, it can be determined which $T_o$ should be increased and which $T_o$ should be decreased in order to produce a higher ball speed at release.

An increase of 2.7% in ball speed was observed when the increased $T_o$ was allowed to vary by ±30%. The upper trunk extension and flexion, scapula external rotation, right upper arm flexion, right upper arm adduction and right upper arm external rotation were increased by more than 5%. Whereas, the $T_o$ values for upper trunk internal rotation, scapula internal rotation, upper arm internal rotation, right upper arm extension and right upper arm abduction decreased by more than 5%. Due to the segments interactions, a greater torque value in one joint orientation will affect another joint orientation which causes the joint orientation to compensate in order to produce a higher ball speed at release.

Based on these findings, pitchers are suggested to improve trunk and upper arm strength (Stodden et al., 2005) and scapula flexibility (Veeger et al., 1993) to maximise pitching velocity.

7.5 Chapter Summary

In this chapter, a torque-driven simulation model of overarm throwing has been applied to answer research questions regarding the technique of overarm throwing in fastball pitching. The optimisations have shown that there was a potential for the pitcher to increase the ball speed through technique changes. Further optimisations have also found that an increase in strength will lead to a small increase in performance.
CHAPTER 8

SUMMARY AND DISCUSSION

8.1 Introduction

In this final chapter, the present study is reviewed to determine whether the purpose of the research has been addressed through the development, evaluation and application of a simulation model of overarm throwing. In addition, the research questions posed in the Chapter 1 are addressed. The limitations and improvements to the techniques used in this study will then be considered followed by future applications to the study.

8.2 Research Summary

The pitching motion is a complex sequence of movements involving the transfer of momentum from the lower extremity to the upper extremity and finally to the ball. The time between front foot contact and ball release is about 0.145 seconds (Stodden et al., 2008) followed by an additional half second for the ball to reach the home plate (Escamilla et al., 1998). Previous studies have shown that the shoulder joint and elbow joint are prone to high risk of injuries due to the rapid and repetitive motion of overarm throwing in fastball pitching (Andrews and Timmerman, 1995; Klingele and Kocher, 2002; Petty et al., 2004; Solomito et al., 2015). Alterations in pitching kinematics will alter the pitching kinetics. Any changes in pitching kinetics are likely to exert excessive force on muscles or ligaments which have an effect on joint load and injury risk. Studies have proposed that pitching types, pitching counts, and pitching mechanics have an influence on the issue of joint load and injury risk (Feltner and Dapena, 1986; Fleisig et al., 1995; Lyman et al., 2002). Thus study on pitching mechanics has a massive impact to tackle the issue of joint load and injury
risk (Atwater, 1979; Feltner and Dapena, 1986; Fleisig et al., 2009; Naito et al., 2012). However, the focus of this study will be on the pitching mechanics to help make improvements in fastball pitching performance rather than to help to reduce the risk of injury.

8.2.1 Computer Simulation Model of Overarm Throwing

The aim of this study was to understand the mechanics of overarm throwing specifically in fastball pitching. To achieve this aim, a computer simulation model of the overarm throwing was developed using Autolev™ (Chapter 4). The three-dimensional model consisted of eight segments. Extensor and flexor torques acted at the upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper external/internal rotation. The pelvis, upper trunk abduction/adduction, left upper arm, left and right forearm, and left and right hand were angle-driven. In the future, torque profiles could be included at the angle-driven joints to provide a more general analysis of overarm throwing. Therefore, their effect on performance can be observed.

Assuming the ball slipped to the fingers at release, the ball was attached at the distal end of the hand with a linear spring to simulate the interaction between hand and ball. This allowed the calculation of ball position and velocity in each direction throughout the movement.

The trunk (referred as upper trunk throughout the thesis) of the pitcher within the simulation model was denoted by one segment which also incorporated the head. This representation of the trunk as one segment is not an accurate representation of the spine, which can bend along its length. Additionally, the clavicular motion was also modelled as one segment (referred as scapula throughout the thesis). This is not a true representation of the shoulder complex, which can rotate independently about the spine. The angle between the head + upper trunk and the left hand + left forearm were constrained to be the same as suggested by analysis of kinematic data. Again, these are not a true representation because the head can rotate about the spine and
left hand can rotate about the left forearm. All of these representations are however, a compromise between accuracy and simplicity which is supported by the fact the model was shown to be able to reproduce the important features of overarm throwing during the model evaluation (Chapter 6).

The other limitation of the simulation model is that the body was considered to be composed of rigid segments. In reality, there is motion of soft tissue relative to the rigid skeletal elements. In order to more accurately represent soft tissue motion, wobbling masses could be incorporated into the model. However, as the model doesn’t involve any high impact movement and was able to match recorded performances reasonably well, omissions of the soft tissue from the model were not likely to have had a substantial effect on the results.

8.2.2 Performance Data

A fastball pitcher was chosen to perform overarm throwing movements. A sixteen camera Vicon motion analysis system operating at 300 Hz was used to track forty-seven retro-reflective markers attached over bony landmarks on the fastball pitcher. Joint centres were determined from the position of these markers and Vicon BodyBuilder software was used to calculate the three degrees-of-freedom angle using the Cardan-Euler three-dimension coordinates (Section 4.5).

8.2.3 Determination of Model Parameters

Due to the difficulty in experimentally measuring the strength parameters for three-dimensional movements (especially the upper trunk external/internal rotation and scapula external/internal rotation), maximal voluntary joint torques were initially estimated by taking average maximal voluntary joint torques from previous studies. By varying $T_o$ and the activation parameters in matching simulation, a new set of maximum voluntary joint torques were obtained. The limitation of this method is that it takes a longer period of time to find a new set of parameters which suitably represent the strength of the pitcher. Because of this limitation, the torque-profile for each segment was solely constructed on the torque-angular velocity relationship and
does not account for the whole muscle-tendon complex. However in this study, the model produces a reasonable output when compared to the performance (Chapter 6). In future it will be ideal if the torque-angle relationship was incorporated in the model so that its effect on the performance of the pitcher can be investigated.

8.2.4 Anthropometric Data

Yeadon’s inertia model (1990a) was used to determine the subject-specific segmental inertia parameters. Previous simulation models have used this model to calculate body segment parameters and have been shown to realistically reproduce human movement (Allen et al., 2012; Jackson, 2010; Kentel, 2009; Wilson et al., 2006). In future, imaging techniques such as CT scanner (Huang and Wu, 1976) or MRI (Martin et al., 1989) could be used to get a more accurate estimation of segmental composition and inertia parameters.

8.2.5 Evaluation of the Torque-Driven Model

Simulated Annealing (Corana et al., 1987) was used in each optimisation of the simulation model. The torque-driven model of overarm throwing was matched to a recorded performance by allowing the $T_0$ and the activation levels of each torque generator to vary. In the model evaluation (Chapter 6), the matching simulation gives a poor match with elbow/forearm extension/flexion torque-driven. Based on the previous studies, the high angular velocity of the elbow prior to ball release was resulted by the centripetal effect due to the rotation of the pelvis, trunk and upper arm (Fleisig and Escamilla, 1996; Werner et al., 1993). Therefore, the elbow/forearm extension/flexion was kept angle-driven.

The simulations matched the performance with an overall difference of 13%. Therefore, the simulation model of overarm throwing was able to reproduce reasonable kinematics of the movement and was suitable to investigate the research questions. Although Simulated Annealing (Corana et al., 1987) is a robust algorithm to find global optimum times, it has relatively poor time efficiency. To run a simulation model requires 3-6 days depends on the number of parameters and the
total number of simulations. Using another algorithm in the future, i.e. a genetic algorithm (Carroll, 2001) may decrease the overall time to find a better set of parameters as well as decreasing the total number of simulations.

8.3 Research Questions

The research questions posed in Chapter 1 were addressed in detail in Chapter 7. The torque-driven simulation model was used in conjunction with a Simulated Annealing to optimise overarm throwing performance, and was also applied to further understanding of the mechanics of fastball pitching. The research questions are restated below and the results are summarised.

1. What complexity of torque-driven simulation model is required to accurately simulate overarm throwing?

The angles from fifteen trials and the angle-driven model were used to analyse the complexity required to develop a torque-driven model (Chapter 4). Every joint orientation (which will also be referred to as segment orientation/angle throughout the thesis) and the difference in ball speed in each axis were examined. Although some of the joint orientations give a small difference in ball speed in each axis, the angles from fifteen trials were reanalysed to observe the significance of that particular joint orientation to the ball speed. If the slope of the curve is higher prior to ball release, the joint orientation will be torque-driven. On the other hand, the angles which are constant prior to ball release or reach zero at ball release were considered angle-driven unless the differences in ball speed are higher. Based on these thorough investigations, it was decided that the upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction, right upper arm external/internal rotation and right forearm extension/flexion will be torque-driven while the rest of the joint orientation will be angle-driven.
2. How close to optimal is the technique of the fastball pitcher in this study?

The optimal technique within this study was considered to be one in which the ball release speed was maximised. There is a potential increase of 14% with a change of technique during the overarm throwing movement. The optimal technique suggests that greater upper trunk flexion, scapula internal rotation, right upper arm flexion and right upper arm external rotation would contribute to an increase in the ball speed at release.

3. How does a 5% increase in strength affect ball release speed?

An optimisation with a 5% increase in the strength of upper trunk extension/flexion, upper trunk external/internal rotation, scapula external/internal rotation, right upper arm flexion/extension, right upper arm adduction/abduction and right upper arm external/internal rotation resulted in a 0.6% increase in resultant speed at ball release. The scapula external/internal rotation, right upper arm flexion/extension and right upper arm abduction/adduction shows a different trend prior to ball release when the strength was increased by 5%. However, right upper arm adducted more at ball release which is presumably an indicator to a small increment in resultant velocity.

4. How does a ±30% change in strength affect ball release speed?

Varying all torque generators by ±30% resulted in an increase of 2.7% in ball speed at release. The scapula internal rotation, right upper arm abduction and right upper arm extension are slightly higher at ball release. The upper trunk extension/flexion shows a slight decreased throughout the movement. Additionally, the $T_o$ values for upper trunk extension and flexion, scapula external rotation, right upper arm flexion, right upper arm adduction and right upper arm external rotation increased more than 5%. On the other hand, the $T_o$ values for upper trunk internal rotation, scapula
internal rotation, right upper arm extension and right upper arm abduction dropped more than 5%. The $T_o$ values for upper trunk external rotation and right upper arm internal rotation show a small decrease. This result shows the segment interactions occur in the kinetic chain. Although not all torque generators benefited from a greater than 5% increase in strength, a decrease in some torque generators values was necessary in order to produce higher ball speed at release.

**8.4 Future Work**

The findings of this study suggest that increasing the strength of the trunk and upper arm is beneficial along with increased scapular flexibility. This is in agreement with some literature where pitchers are suggested to improve trunk and upper arm strength (Stodden et al., 2005) and scapula flexibility (Veeger et al., 1993) to maximise pitching velocity. To further understand these relationships new experimental studies which can be done; for example take a group of pitchers and investigate the effects of a specific strength training programme / flexibility programme on pitching velocity. Coaches can make use of all the information gained to design appropriate strength training, training skills, tactics and strategies for the pitchers.

As the simulation model of the overarm throwing has been successfully evaluated, it can be used to further investigate the mechanics of fastball pitching. Additional research questions that could be addressed using the simulation model include:

- How does the individual strength of each joint affect overarm throwing?

Based on previous studies, increasing trunk, upper arm and forearm strength is necessary to maximise ball speed at release (Solomito et al., 2015; Stodden et al., 2005). However, it is almost impossible to investigate the effect of individual strength of each joint in overarm throwing through experiment. Therefore, the simulation model can be used to investigate the effect of the individual strength of each joint in overarm throwing. Coaches can make use
of all the information gained to design appropriate strength training for the pitchers.

- How do altered anthropometric and mass/inertia characteristics affect overarm throwing?

The timing of onset of joint torques in overarm throwing is sensitive to segmental dimensions and inertia characteristics (Herring and Chapman, 1992). The proximal-to-distal sequence of onset of joint torques and peaking of joint angular velocities proved best in maximising ball range and velocity regardless of changes in segmental masses and lengths (Chapman, 1985; Herring and Chapman, 1992; Putnam, 1983). Simulations and experimental studies can be carried out to investigate how the three-dimensional overarm throwing will be affected if the anthropometric and mass/inertia characteristics are altered.

- How does different body mass/size affect overarm throwing?

Body size had a strong positive effect on the throwing performance and isometric strength. Throwing velocity appeared to be affected by gender when size was expressed by mass or height (Escamilla et al., 2002; Tillaar and Ettema, 2004; Werner et al., 2008). Approximately 50% of the variability in ball velocity was explained by anthropometric variables, with body mass being the most predictive in determining ball velocity (Escamilla et al., 2002; Matsuo et al., 2001). Simulations and experimental studies can be carried out to investigate how the differences in the body mass/size will effect overarm throwing.
• How sensitive is the direction and magnitude of the ball speed to the positioning of ball on the hand?

Until recently, there is no standard system with simulation models to determine the position of the ball in overarm throwing. The position of the ball is either assumed to be at the wrist (Matsuo et al., 2002) or at metacarpophalangeal (MP) joint (Naito et al., 2011). Yet, the sensitivity of the direction and magnitude of the ball speed to the positioning of ball on the hand is not known. Therefore, the simulation model of overarm throwing can be used to tackle this issue.

• How sensitive is overarm throwing performance to variations in muscle activation timings?

The coordination of joint and muscle actions is often considered to be crucial to the successful execution of throwing movements. Previous studies were focused on the proximal-to-distal sequencing of muscle activations (Chowdhary and Challis, 2001; Hirashima et al., 2002) in maximising speed. However, the simulation model developed by Chowdhary and Challis (2001) was only a two-segment planar model which is inadequate to represent the overarm throwing. Three-dimensional simulation models can be used to counter this limitation. On the other hand, an experimental study done by Hirashima et al. (2002) was limited to investigate muscle activities at abdomen and upper extremities. Hence, experimental studies can be done to investigate whole body muscle activities in overarm throwing.

• What impact does the torque-angle relationship have on overarm throwing?

It is preferable that torque generators have Hill-type characteristics in order to obtain reasonable simulations of human movement (Fujii and Hubbard, 2002). The limitation of the simulation model in this study is the torque-
angle relationship was not included although the simulations matched the performance with an overall difference of 13%. In future, the simulation model will include the torque-angle relationship. Subsequently, the impact of the torque-angle relationship on overarm throwing can be investigated.

- How does the technique in overarm technique altered when elbow/forearm is torque-driven?

The main the limitation of this study is that the elbow/forearm is kept-angle driven throughout the technique and strength optimisations (Chapter 7). The results obtained from the technique and strength optimisations shows that apart from the trunk flexion at ball release, scapula too plays an important role in maximising the ball speed at release. However, since the elbow/forearm is kept angle-driven, momentum transferred from the scapula to the upper arm to the forearm through the shoulder and elbow is not optimal as the elbow movement is constrained to that used in the performance. According to Stodden et al. (2005), pitchers should strengthen shoulder and elbow musculature that resist distraction as well as improve trunk strength and flexibility to maximise pitching velocity and help prevent injury. It is intended to change the elbow to be torque-driven and all the issues regarding elbow raised in Chapter 6 will be addressed. Therefore in the future, the contribution of the elbow to the overarm throwing can be discovered, along with fully understanding the mechanics of overarm throwing. Coaches can make use of all the information gained to design appropriate training skills, tactics and strategies for the pitchers.

### 8.5 Conclusions

The aim of this research was to analyse overarm throwing to gain an improved understanding of the mechanics of fastball pitching, subsequently to use this understanding to identify ways to improve performance. To achieve this, at first an
angle-driven model was advanced to substantiate the model complexity for use in the torque-driven model. After a systematic procedure of examining model complexity, a torque-driven simulation model of overarm throwing was developed. The torque-driven model was successfully evaluated and shown to produce realistic movements. The model was then applied to further the understanding of the mechanics of fastball pitching. The optimised technique employed by the simulation model agreed with features demonstrated by current elite pitchers and confirmed previous research which was encouraging and a further indication of the accuracy of the model. Finally the model was used to show that increasing strength increased ball release speed by a small amount and there is a possibility to increase ball release speed if the increased strength was allowed to vary.
REFERENCES


Nissen, C., Westwell, M., Ounpuu, S., Patel, M., Tate, J. P., Pierz, K., Burns, J. P. and Bicos, J. (2007). Adolescent baseball pitching technique: a detailed three-


APPENDIX A

ANGLES OBTAINED FROM 15 TRIALS

This section presents joint angles obtained from fifteen trials. Ball release at time zero.

Figure A1: Orientation of pelvis about x-axis, y-axis and z-axis, respectively.
Figure A2: Orientation of upper trunk about x-axis, y-axis and z-axis, respectively.
Figure A3: Orientation of scapula about y-axis and z-axis, respectively.
Figure A4: Orientation of right upper arm about x-axis, y-axis and z-axis, respectively.
Figure A5: Orientation of right forearm about x-axis, y-axis and z-axis, respectively.
Figure A6: Orientation of right forearm about x-axis and y-axis, respectively.
Figure A7: Orientation of left upper arm about x-axis, y-axis and z-axis, respectively.
**Figure A8:** Orientation of left forearm about x-axis.
APPENDIX B

AUTOLEV CODE

Torque-driven model of overarm throwing

%===================================================================
% This code is written by Nurhidayah Omar for study on throwing.
% Assumptions: 1) trunk + head
% 2) nonthrowing forearm + hand
%===================================================================
% This is the first model - torque generator was included at
% 1) trunk flexion/extension
% 2) trunk twist
% 3) shoulder girdle twist
% 4) right shoulder flexion/extension
% 5) right shoulder int/ext rotation
% 6) right shoulder add/abd
%===================================================================
% This model comprises of 23 DOF and eight segments (pelvis, trunk
% plus head, shoulder girdle, throwing arm (upper arm, forearm and
% hand) and non-throwing (upper arm and forearm plus hand).
% 6DOF describing rotation and translation of pelvis about global,
% 3DOF describing rotation of trunk and 3DOF describing
% rotation of shoulder girdle.
% For throwing arm: 3DOF describing rotation of upper arm, 3DOF
% describing rotation of forearm and 2DOF describing rotation of
% hand.
% For non-throwing arm: 3DOF representing rotation of upper arm and
% 1DOF to describe rotation of forearm.
% z-axis (3rd axis) is the vertical axis, y-axis (2nd axis) is the 
% horizontal axis towards home-plate (throwing direction) and 
% x-axis (1st axis) is the medial/lateral axis.

%===================================================================
NEWTONIAN N %Newtonian reference frame
AUTOZ on %Simplifies the output equations
%===================================================================

% Physical declarations: bodies, frames, points and particles

%===================================================================
BODIES A,B,BH,C,D,E,H,L,M,MF
POINTS O,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11,P12,P13
PARTICLES J
%===================================================================

MASS A=MA %Mass of pelvis (segment A)
MASS B=MB %Mass of trunk (segment B)
MASS BH=MBH %Mass of head (segment BH)
MASS C=MC %Mass of shoulder girdle (segment C)
MASS D=MD %Mass of upper arm (segment D)
MASS E=ME %Mass of forearm (segment E)
MASS H=MH %Mass of hand (segment F)
MASS L=ML %Mass of free upperarm (segment L)
MASS M=MM %Mass of free forearm (segment M)
MASS MF=MMF %Mass of free hand (segment MF)
MASS J=MJ %Mass of particle (ball)

INERTIA A,IA1,IA2,IA3 %Moment-of-inertia of A
INERTIA B,IB1,IB2,IB3 %Moment-of-inertia of B
INERTIA BH,IBH1,IBH2,IBH3 %Moment-of-inertia of BH
INERTIA C,IC1,IC2,IC3 %Moment-of-inertia of C
INERTIA D,ID1,ID2,ID3 %Moment-of-inertia of D
INERTIA E,IE1,IE2,IE3 %Moment-of-inertia of E
INERTIA H,IH1,IH2,IH3 %Moment-of-inertia of H
INERTIA L,IL1,IL2,IL3 %Moment-of-inertia of L
INERTIA M,IM1,IM2,IM3 %Moment-of-inertia of M
INERTIA MF,IMF1,IMF2,IMF3 %Moment-of-inertia of MF

%===================================================================
CONSTANTS G %Gravity
CONSTANTS NANG %head position
CONSTANTS MANG %nonthrowing hand position
CONSTANTS K(2) %constant spring
CONSTANTS LAO, LA %Length of pelvis
CONSTANTS LBO, LB %Length of trunk
CONSTANTS LBHO, LBH %Length of head
CONSTANTS LCO, LC %Length of shoulder girdle
CONSTANTS LDO, LD %Length of throwing upperarm
CONSTANTS LEO, LE %Length of throwing forearm
CONSTANTS LHO, LH %Length of throwing hand
CONSTANTS LLO, LL %Length of nonthrowing upperarm
CONSTANTS LMO, LM %Length of nonthrowing forearm
CONSTANTS LMFO, LMF %Length of nonthrowing hand

%===================================================================
% Mathematical declarations: Generalised coordinates and generalised
% speed
%===================================================================
VARIABLES Q1', Q2', Q3' %origin (midpoint pelvis)
%VARIABLES Q4', Q5', Q6' %angle and angular speed of pelvis
%VARIABLES Q8' %angle and angular speed of trunk
VARIABLES Q7', Q9' %tor gen at trunk (1st & 3rd rot)
%VARIABLES Q10', Q23' %shoulder girdle
VARIABLES Q12', Q13' %tor gen at shoulder girdle (3rd rot)
%VARIABLES Q14', Q15', Q16' %angle and angular speed of elbow
%VARIABLES Q17', Q18', Q19' %angle and angular speed of wrist
VARIABLES Q20', Q21', Q22' %position of hand
%VARIABLES Q24', Q25', Q26' %angle and angular speed of f.shoulder
%VARIABLES Q27' %angle and angular speed of f.elbow
VARIABLES U{28}' specified TRA1'', TRA2'', TRA3''
specified THETA1'', THETA2''
specified ANG4'', ANG5'', ANG6''
specified ANG8''
specified ANG12''
specified ANG14'', ANG15'', ANG16''
specified ANG17'', ANG18'', ANG19''
specified ANG24'', ANG25'', ANG26''
specified ANG27''
specified TOR7, TOR9, TOR28, TOR11, TOR12, TOR13

%===================================================================
% Declare additional variables
%===================================================================
VARIABLES RX,RY,RZ %Force to hold Midpoint pelvis
VARIABLES RX1,RY1,RZ1 %Hand/Particle force

VARIABLES TOR4,TOR5,TOR6,TOR8,TOR10,TOR14,TOR15,TOR16,TOR18,TOR19,TOR23,
TOR24,TOR25,TOR26,TOR27

ZEE_NOT=[RX,RY,RZ,TOR4,TOR5,TOR6,TOR8,TOR10,TOR14,TOR15,TOR16,TOR18,
TOR19,TOR23,TOR24,TOR25,TOR26,TOR27]

%===================================================================
% Kinematic differential equations
%===================================================================
Q1'=U1
Q2'=U2
Q3'=U3
Q7'=U7
Q9'=U9
Q11'=U11
Q12'=U12
Q13'=U13
TRA1 = T^3
TRA2 = T^3
TRA3 = T^3
TRA1'' = dt(TRA1')
TRA2'' = dt(TRA2')
TRA3'' = dt(TRA3')
Q20'=U20
Q21'=U21
Q22'=U22
Q28'=U28

%===================================================================
% Position vectors and direction cosine matrices
%===================================================================
% Segment 1(A) - pelvis

dircos(N,A,BODY123,ANG4,ANG5,ANG6)
P_O_P1> = Q1*N1> + TRA1*N1> + Q2*N2> + TRA2*N2> + Q3*N3> + TRA3*N3>
P_P1_AO> = LAO*A1>

P_P1_P2> = 0.4*LA*A1>
P_P1_P3> = -0.4*LA*A1>
P_O_P1X=DOT(P_O_P1>,N1>)
P_O_P1Y=DOT(P_O_P1>,N2>)
\[
\begin{align*}
\text{P}_\text{O}_\text{P}_1\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{P}_1, \text{N}_3) \\
\text{P}_\text{O}_\text{A}_\text{O} &= \text{P}_\text{O}_\text{P}_1 + \text{P}_\text{P}_1\text{A}_\text{O} \\
\text{P}_\text{O}_\text{P}_2 &= \text{P}_\text{O}_\text{P}_1 + \text{P}_\text{P}_1\text{P}_2 \\
\text{P}_\text{O}_\text{P}_3 &= \text{P}_\text{O}_\text{P}_1 + \text{P}_\text{P}_1\text{P}_3 \\
\text{POA}_\text{O}_\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{A}_\text{O}, \text{N}_1) \\
\text{POA}_\text{O}_\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{A}_\text{O}, \text{N}_2) \\
\text{POA}_\text{O}_\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{A}_\text{O}, \text{N}_3) \\
\text{POP}_2\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{P}_2, \text{N}_1) \\
\text{POP}_2\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{P}_2, \text{N}_2) \\
\text{POP}_2\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{P}_2, \text{N}_3) \\
\text{POP}_3\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{P}_3, \text{N}_1) \\
\text{POP}_3\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{P}_3, \text{N}_2) \\
\text{POP}_3\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{P}_3, \text{N}_3)
\end{align*}
\]

% Segment 2(B) - trunk + head
\[
\text{dircos}(\text{B}, \text{A}, \text{BODY321}, -\text{Q}9, -\text{ANG}8, -\text{Q}7)
\]
\[
\begin{align*}
\text{P}_\text{P}_1\text{B}_\text{O} &= 1\times\text{LB}_\text{B} \times \text{B}_3 \\
\text{P}_\text{P}_1\text{P}_4 &= 1\times\text{LB} \times \text{B}_3 \\
\text{P}_\text{O}_\text{B}_\text{O} &= \text{P}_\text{O}_\text{P}_1 + \text{P}_\text{P}_1\text{B}_\text{O} \\
\text{P}_\text{O}_\text{P}_4 &= \text{P}_\text{O}_\text{P}_1 + \text{P}_\text{P}_1\text{P}_4 \\
\text{POB}_\text{O}_\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{O}, \text{N}_1) \\
\text{POB}_\text{O}_\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{O}, \text{N}_2) \\
\text{POB}_\text{O}_\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{O}, \text{N}_3) \\
\text{POP}_4\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{P}_4, \text{N}_1) \\
\text{POP}_4\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{P}_4, \text{N}_2) \\
\text{POP}_4\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{P}_4, \text{N}_3)
\end{align*}
\]

% simprot(B,H,1,NANG)
\[
\begin{align*}
\text{P}_\text{P}_4\text{B}_\text{H} &= \text{LB}_\text{H} \times \text{B}_3 \\
\text{P}_\text{P}_4\text{P}_12 &= \text{LB}_\text{H} \times \text{B}_3 \\
\text{P}_\text{O}_\text{B}_\text{H} &= \text{P}_\text{O}_\text{P}_4 + \text{P}_\text{P}_4\text{B}_\text{H} \\
\text{P}_\text{O}_\text{P}_12 &= \text{P}_\text{O}_\text{P}_4 + \text{P}_\text{P}_4\text{P}_12 \\
\text{POB}_\text{H}_\text{O}_\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{H}, \text{N}_1) \\
\text{POB}_\text{H}_\text{O}_\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{H}, \text{N}_2) \\
\text{POB}_\text{H}_\text{O}_\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{B}_\text{H}, \text{N}_3) \\
\text{POP}_12\text{X} &= \text{DOT}(\text{P}_\text{O}_\text{P}_12, \text{N}_1) \\
\text{POP}_12\text{Y} &= \text{DOT}(\text{P}_\text{O}_\text{P}_12, \text{N}_2) \\
\text{POP}_12\text{Z} &= \text{DOT}(\text{P}_\text{O}_\text{P}_12, \text{N}_3)
\end{align*}
\]
% Segment 3(C) - shoulder girdle

dircos(C,B,BODY321,-Q28,-THETA2,-THETA1)
P_P4_CO> = LCO*C1>
P_P4_P5> = 0.7*LC*C1>
P_P4_P6> = -0.7*LC*C1>
P_O_CO> = P_O_P4> + P_P4_CO>
P_O_P5> = P_O_P4> + P_P4_P5>
P_O_P6> = P_O_P4> + P_P4_P6>
P_P5_CO> = LDO*D3>
P_P5_P7> = L*E3>
P_O_DO> = P_O_P5> + P_P5_DO>
P_O_P7> = P_O_P5> + P_P5_P7>
PODOX = DOT(P_O_DO>,N1>)
PODOY = DOT(P_O_DO>,N2>)
PODOZ = DOT(P_O_DO>,N3>)
P_POP5X = DOT(P_O_P5>,N1>)
P_POP5Y = DOT(P_O_P5>,N2>)
P_POP5Z = DOT(P_O_P5>,N3>)
P_POP6X = DOT(P_O_P6>,N1>)
P_POP6Y = DOT(P_O_P6>,N2>)
P_POP6Z = DOT(P_O_P6>,N3>)

% Segment 4(D) - upper arm (throwing arm)

dircos(D,C,BODY321,-Q13,-Q12,-Q11)
P_P5_DO> = -LDO*D3>
P_P5_P7> = -L*E3>
P_O_DO> = P_O_P5> + P_P5_DO>
P_O_P7> = P_O_P5> + P_P5_P7>
PODOX = DOT(P_O_DO>,N1>)
PODOY = DOT(P_O_DO>,N2>)
PODOZ = DOT(P_O_DO>,N3>)
P_POP7X = DOT(P_O_P7>,N1>)
P_POP7Y = DOT(P_O_P7>,N2>)
P_POP7Z = DOT(P_O_P7>,N3>)

% Segment 5(E) - forearm (throwing arm)

dircos(E,D,BODY321,-ANG16,-ANG15,-ANG14)
P_P7_EO> = -LEO*E3>
P_P7_P8> = -LE*E3>
P_O_EO> = P_O_P7> + P_P7_EO>
\[ P_{O\ P8} = P_{O\ P7} + P_{P7\ P8} \]
\[ POEX = DOT(P_{O\ EO}>,N1>) \]
\[ POEY = DOT(P_{O\ EO}>,N2>) \]
\[ POEZ = DOT(P_{O\ EO}>,N3>) \]
\[ POP8X = DOT(P_{O\ P8}>,N1>) \]
\[ POP8Y = DOT(P_{O\ P8}>,N2>) \]
\[ POP8Z = DOT(P_{O\ P8}>,N3>) \]

% Segment 6 (H) - hand (throwing arm)

\[ \text{dircos}(H,E,\text{BODY321},-\text{ANG19},-\text{ANG18},-\text{ANG17}) \]
\[ P_{P8\ HO} = -1*\text{LHO}*H3> \]
\[ P_{P8\ P9} = -1.0*\text{LH}*H3> \]
\[ P_{O\ HO} = P_{O\ P8} + P_{P8\ HO} \]
\[ P_{O\ P9} = P_{O\ P8} + P_{P8\ P9} \]
\[ POHOX = DOT(P_{O\ HO}>,N1>) \]
\[ POHOY = DOT(P_{O\ HO}>,N2>) \]
\[ POHOZ = DOT(P_{O\ HO}>,N3>) \]
\[ POP9X = DOT(P_{O\ P9}>,N1>) \]
\[ POP9Y = DOT(P_{O\ P9}>,N2>) \]
\[ POP9Z = DOT(P_{O\ P9}>,N3>) \]

% Position of hand and ball

\[ P_{P9\ J} = Q20*N1> + Q21*N2> + Q22*N3> \]
\[ P_{O\ J} = P_{O\ P9} + P_{P9\ J} \]
\[ POJX = DOT(P_{O\ J}>,N1>) \]
\[ POJY = DOT(P_{O\ J}>,N2>) \]
\[ POJZ = DOT(P_{O\ J}>,N3>) \]

% Segment 7 (L) - upper arm (free arm)

\[ \text{dircos}(L,C,\text{BODY321},-\text{ANG26},-\text{ANG25},-\text{ANG24}) \]
\[ P_{P6\ LO} = -1*\text{LLO}*L3> \]
\[ P_{P6\ P10} = -1*\text{LL}*L3> \]
\[ P_{O\ LO} = P_{O\ P6} + P_{P6\ LO} \]
\[ P_{O\ P10} = P_{O\ P6} + P_{P6\ P10} \]
\[ POLOX = DOT(P_{O\ LO}>,N1>) \]
\[ POLOY = DOT(P_{O\ LO}>,N2>) \]
\[ POLOZ = DOT(P_{O\ LO}>,N3>) \]
\[ \text{POP10x} = \text{DOT} (\text{P}_O\text{P10}, \text{N1}) \]
\[ \text{POP10y} = \text{DOT} (\text{P}_O\text{P10}, \text{N2}) \]
\[ \text{POP10z} = \text{DOT} (\text{P}_O\text{P10}, \text{N3}) \]

\%---------------------------------------------------------------
\%
\%Segment 9(M) - forearm + hand (free arm)
\%---------------------------------------------------------------
\%
\text{simprot} (L, M, 1, ANG27)
\text{P}_P10\text{MO} = -1*LMO*M3>
\text{P}_P10\text{P11} = -1*LM*M3>
\text{P}_O\text{MO} = \text{P}_O\text{P10} + \text{P}_P10\text{MO}>
\text{P}_O\text{P11} = \text{P}_O\text{P10} + \text{P}_P10\text{P11}>
\text{POMOX} = \text{DOT} (\text{P}_O\text{MO}, \text{N1})
\text{POMOY} = \text{DOT} (\text{P}_O\text{MO}, \text{N2})
\text{POMOZ} = \text{DOT} (\text{P}_O\text{MO}, \text{N3})
\text{POP11x} = \text{DOT} (\text{P}_O\text{P11}, \text{N1})
\text{POP11y} = \text{DOT} (\text{P}_O\text{P11}, \text{N2})
\text{POP11z} = \text{DOT} (\text{P}_O\text{P11}, \text{N3})

\%---------------------------------------------------------------
\%
\text{simprot} (M, MF, 1, MANG)
\text{P}_P11\text{MFO} = -1*LMFO*MF3>
\text{P}_P11\text{P13} = -1*LMF*MF3>
\text{P}_O\text{MFO} = \text{P}_O\text{P11} + \text{P}_P11\text{MFO}>
\text{P}_O\text{P13} = \text{P}_O\text{P11} + \text{P}_P11\text{P13}>
\text{POMFOX} = \text{DOT} (\text{P}_O\text{MFO}, \text{N1})
\text{POMFOY} = \text{DOT} (\text{P}_O\text{MFO}, \text{N2})
\text{POMFOZ} = \text{DOT} (\text{P}_O\text{MFO}, \text{N3})
\text{POP13x} = \text{DOT} (\text{P}_O\text{P13}, \text{N1})
\text{POP13y} = \text{DOT} (\text{P}_O\text{P13}, \text{N2})
\text{POP13z} = \text{DOT} (\text{P}_O\text{P13}, \text{N3})

\%---------------------------------------------------------------
\%
\% Linear and Angular velocities
\%---------------------------------------------------------------
\%
\% Segment 1(A) - pelvis
\%---------------------------------------------------------------
\%
\text{W}_A\text{N} = (\cos(\text{ANG5})*\cos(\text{ANG6})*\text{ANG4'}+\sin(\text{ANG6})*\text{ANG5'})*A1> + U4*A1> +
(-\cos(\text{ANG5})*\sin(\text{ANG6})*\text{ANG4'}+\cos(\text{ANG6})*\text{ANG5'})*A2> + U5*A2> +
(\sin(\text{ANG5})*\text{ANG4'}+\sin(\text{ANG6}'))*A3> + U6*A3>
\text{V}_O\text{N} = 0>
\text{V}_P1\text{N} = \text{DT} (\text{P}_O\text{P1}, \text{N})
\text{V2PTS} (N, A, P1, AO)
\text{V2PTS} (N, A, P1, F2)

183
\begin{verbatim}
V2PTS(N,A,P1,P3)
VOP1X = DOT(V_P1_N>,N1>)
VOP1Y = DOT(V_P1_N>,N2>)
VOP1Z = DOT(V_P1_N>,N3>)
VOAOX = DOT(V_AO_N>,N1>)
VOAOY = DOT(V_AO_N>,N2>)
VOAOZ = DOT(V_AO_N>,N3>)
VOP2X = DOT(V_P2_N>,N1>)
VOP2Y = DOT(V_P2_N>,N2>)
VOP2Z = DOT(V_P2_N>,N3>)
VOP3X = DOT(V_P3_N>,N1>)
VOP3Y = DOT(V_P3_N>,N2>)
VOP3Z = DOT(V_P3_N>,N3>)

%------------------------------------------------------
% Segment 2(B) - trunk + head
%------------------------------------------------------

W_B_A> = (COS(ANG8)*COS(Q9)*U7+SIN(Q9)*ANG8')*B1> + (-
COS(ANG8)*SIN(Q9)*U7+COS(Q9)*ANG8')*B2> + U8*B2> +
(SIN(ANG8)*U7+U9)*B3>
V2PTS(N,B,P1,BO)
V2PTS(N,B,P1,P4)
VOBOX = DOT(V_BO_N>,N1>)
VOBOY = DOT(V_BO_N>,N2>)
VOBOZ = DOT(V_BO_N>,N3>)
VOP4X = DOT(V_P4_N>,N1>)
VOP4Y = DOT(V_P4_N>,N2>)
VOP4Z = DOT(V_P4_N>,N3>)

%------------------------------------------------------
% Segment 3(C) - shoulder girdle
%------------------------------------------------------

W_C_B> = (COS(THETA2)*COS(Q28)*THETA1'+SIN(Q28)*THETA2')*C1> +
U10*C1> + (-COS(THETA2)*SIN(Q28)*THETA1'+COS(Q28)*THETA2')*C2> +
U23*C2> + (SIN(THETA2)*THETA1'+U28)*C3>
V2PTS(N,C,P4,CO)
V2PTS(N,C,P4,P5)
V2PTS(N,C,P4,P6)
VOCOX = DOT(V_CO_N>,N1>)
\end{verbatim}
\[\text{VOCOY} = \text{DOT}(V_{CO_N'},N2')\]
\[\text{VOCOZ} = \text{DOT}(V_{CO_N'},N3')\]
\[\text{VOP5X} = \text{DOT}(V_{P5_N'},N1')\]
\[\text{VOP5Y} = \text{DOT}(V_{P5_N'},N2')\]
\[\text{VOP5Z} = \text{DOT}(V_{P5_N'},N3')\]
\[\text{VOP6X} = \text{DOT}(V_{P6_N'},N1')\]
\[\text{VOP6Y} = \text{DOT}(V_{P6_N'},N2')\]
\[\text{VOP6Z} = \text{DOT}(V_{P6_N'},N3')\]

% Segment 4(D) - upper arm (throwing arm)

% Segment 5(E) - forearm (throwing arm)

% Segment 6(H) - hand (throwing arm)
V2PTS(N,H,P8,P9)
V2PTS(N,L,P6,LO)
V2PTS(N,M,P10,M0)
V2PTS(N,MF,P11,M0)

Vohox = DOT(V_HO_N>,N1>)
Vohoy = DOT(V_HO_N>,N2>)
Vohoz = DOT(V_HO_N>,N3>)
Vop9x = DOT(V_P9_N>,N1>)
Vop9y = DOT(V_P9_N>,N2>)
Vop9z = DOT(V_P9_N>,N3>)

V_J_N> = DT(P_O_J>,N)
VoJx = DOT(V_J_N>,N1>)
VoJy = DOT(V_J_N>,N2>)
VoJz = DOT(V_J_N>,N3>)

% Segment 8(L) - upper arm (free arm)

W_L_C> = (COS(ANG25)*COS(ANG26)*ANG24'+SIN(ANG26)*ANG25')*L1> + U24*L1> + (-COS(ANG25)*SIN(ANG26)*ANG24'+COS(ANG26)*ANG25')*L2> + U25*L2> + (SIN(ANG25)*ANG24'+ANG26')*L3> + U26*L3>

% Segment 9(M) - forearm + hand (free arm)

W_M_L> = ANG27'*M1> + U27*M1>

W_MF_M> = 0>

V2PTS(N,MF,P11,M0)
V2PTS(N,MF,P11,P13)
%===================================================================
% Impose motion constraints
%===================================================================
AUXILIARY[1]=U1
AUXILIARY[2]=U2
AUXILIARY[3]=U3
AUXILIARY[4]=U4
AUXILIARY[5]=U5
AUXILIARY[6]=U6
AUXILIARY[7]=U8
AUXILIARY[8]=U10
AUXILIARY[9]=U14
AUXILIARY[10]=U15
AUXILIARY[12]=U17
AUXILIARY[13]=U18
AUXILIARY[14]=U19
AUXILIARY[15]=U23
AUXILIARY[16]=U24
AUXILIARY[17]=U25
AUXILIARY[18]=U26
AUXILIARY[19]=U27
CONSTRAN(AUXILIARY[U1,U2,U3,U4,U5,U6,U8,U10,U14,U15,U16,U17,U18,U19
,U23,U24,U25,U26,U27])
%===================================================================
% Linear and Angular accelerations
%===================================================================
% Segment 1(A) - pelvis
%----------------------------------------------------------------------
ALF_A_N> = DT(W_A_N>,A)
A_O_N> = 0>
A2PTS(N,A,P1,AO)
A2PTS(N,A,P1,P2)
A2PTS(N,A,P1,P3)
A_AO_N> = DT(V_AO_N>,N)
A_P2_N> = DT(V_P2_N>,N)
%----------------------------------------------------------------------
% Segment 2(B) - trunk + head
%----------------------------------------------------------------------
ALF_B_A> = DT(W_B_A>,B)
A2PTS(N,B,F1,B0)
A2PTS(N,B,F1,F4)
A_BO_N> = DT(V_BO_N>,N)
A_P4_N> = DT(V_P4_N>,N)
%---------------------------------------------

ALF_BH_B> = 0>
A2PTS(N,BH,F4,BHO)
A2PTS(N,BH,F4,F12)
%---------------------------------------------

% Segment 3(C) - shoulder girdle
%---------------------------------------------

ALF_C_B> = DT(W_C_B>,C)
A2PTS(N,C,F4,CO)
A2PTS(N,C,F4,F5)
A2PTS(N,C,F4,F6)
A_CO_N> = DT(V_CO_N>,N)
A_P5_N> = DT(V_P5_N>,N)
%---------------------------------------------

% Segment 4(D) - upper arm (throwing arm)
%---------------------------------------------

ALF_D_C> = DT(W_D_C>,D)
A2PTS(N,D,F5,DO)
A2PTS(N,D,F5,F7)
A_DO_N> = DT(V_DO_N>,N)
A_P7_N> = DT(V_P7_N>,N)
%---------------------------------------------

% Segment 5(E) - forearm (throwing arm)
%---------------------------------------------

ALF_E_D> = DT(W_E_D>,E)
A2PTS(N,E,F7,EO)
A2PTS(N,E,F7,F8)
A_EO_N> = DT(V_EO_N>,N)
A_P8_N> = DT(V_P8_N>,N)
%---------------------------------------------

% Segment 6(H) - hand (throwing arm) & ball
%---------------------------------------------

ALF_H_E> = DT(W_H_E>,H)
A2PTS(N,H,F8,HO)
A2PTS(N,H,F8,F9)
A_HO_N> = DT(V_HO_N>,N)
A_P9_N> = DT(V_P9_N>,N)
%---------------------------------------------------------------------
A_J_N> = DT(V_J_N>,N)
%---------------------------------------------------------------------
% Segment 8(L) - upper arm (free arm)
------------------------------------------------------------------------
ALF_L_C> = DT(W_L_C>,L)
A2PTS(N,L,P6,LO)
A2PTS(N,L,P6,P10)
A_LO_N> = DT(V_LO_N>,N)
A_P10_N> = DT(V_P10_N>,N)
%---------------------------------------------------------------------
% Segment 9(M) - forearm plus hand (free arm)
------------------------------------------------------------------------
ALF_M_L> = DT(W_M_L>,M)
A2PTS(N,M,P10,M0)
A2PTS(N,M,P10,P11)
A_MO_N> = DT(V_MO_N>,N)
A_P11_N> = DT(V_P11_N>,N)
%---------------------------------------------------------------------
ALF_MF_M> = 0>
A2PTS(N,MF,P11,MFO)
A2PTS(N,MF,P11,P13)
%===================================================================
% Kinetic and Potential Energy for every segment
%===================================================================
KEA=KE(A)
KEB=KE(B)
KEC=KE(C)
KED=KE(D)
KEE=KE(E)
KEH=KE(H)
KEL=KE(L)
KEM=KE(M)
KEJ=KE(J)
%---------------------------------------------------------------
PEA=-1*MA*G*POAOZ
PEB=-1*MB*G*POBOZ
PEC=-1*MC*G*POCOZ
PED=-1*MD*G*PODOZ
PEE=-1*ME*G*POEOZ
PEH=-1*MH*G*POHOZ
PEL=-1*ML*G*POLOZ
PEM=-1*MM*G*POMOZ
PEJ=-1*MJ*G*POJZ

% Expressions for forces and torques
% TOR10 & TOR19 are calculated but not going to be used
% because need to make sure auxiliary variables equal to in Kane's
%===================================================================
TORQUE(N/A,TOR4*N1>)
TORQUE(N/A,TOR5*N2>)
TORQUE(N/A,TOR6*N3>)
TORQUE(B/A,TOR7*B1>)
TORQUE(B/A,TOR8*B2>)
TORQUE(B/A,TOR9*B3>)
TORQUE(C/B,TOR10*C1>)
TORQUE(C/B,TOR23*C2>)
TORQUE(C/B,TOR28*C3>)
TORQUE(D/C,TOR11*D1>)
TORQUE(D/C,TOR12*D2>)
TORQUE(D/C,TOR13*D3>)
TORQUE(E/D,TOR14*E1>)
TORQUE(E/D,TOR15*E2>)
TORQUE(E/D,TOR16*E3>)
TORQUE(H/E,TOR17*H1>)
TORQUE(H/E,TOR18*H2>)
TORQUE(H/E,TOR19*H3>)
TORQUE(L/C,TOR24*L1>)
TORQUE(L/C,TOR25*L2>)
TORQUE(L/C,TOR26*L3>)
TORQUE(L/M,TOR27*L1>)

% For ball release
STRETCH1=DOT(F_P9_J>,N1>)
STRETCH2=DOT(F_P9_J>,N2>)
STRETCH3=DOT(F_P9_J>,N3>)
VELOCITY1=DT(STRETCH1)
VELOCITY2=DT(STRETCH2)
VELOCITY3=DT(STRETCH3)
RX1=(-K1*STRETCH1-K2*VELOCITY1)
RY1=(-K1*STRETCH2-K2*VELOCITY2)
RZ1=(-K1*STRETCH3-K2*VELOCITY3)

GRAVITY(G*N3>)
FORCE(P1,RX*N1> + RY*N2> + RZ*N3>)
FORCE(P9/J,RX1*N1> + RY1*N2> + RZ1*N3>)

% Equations of motion
ZERO = FR() + FRSTAR()
KANE(RX,RY,RZ,TOR4,TOR5,TOR6,TOR8,TOR10,TOR14,TOR15,TOR16,TOR17,TOR18,TOR19,TOR23,TOR24,TOR25,TOR26,TOR27)

% Declare value for Theta, Phi and angle joints (3rd order, which % are edited in Fortran Code)
THETA1 = T^3
THETA2 = T^3
ANG4 = T^3
ANG5 = T^3
ANG6 = T^3
ANG8 = T^3
ANG14 = T^3
ANG15 = T^3
ANG16 = T^3
ANG17 = T^3
ANG18 = T^3
ANG19 = T^3
ANG24 = T^3
ANG25 = T^3
ANG26 = T^3
ANG27 = T^3
\[ \theta_1'' = dt(\theta_1') \]
\[ \theta_2'' = dt(\theta_2') \]
\[ \alpha_4'' = dt(\alpha_4') \]
\[ \alpha_5'' = dt(\alpha_5') \]
\[ \alpha_6'' = dt(\alpha_6') \]
\[ \alpha_8'' = dt(\alpha_8') \]
\[ \alpha_{14}'' = dt(\alpha_{14}') \]
\[ \alpha_{15}'' = dt(\alpha_{15}') \]
\[ \alpha_{16}'' = dt(\alpha_{16}') \]
\[ \alpha_{17}'' = dt(\alpha_{17}') \]
\[ \alpha_{18}'' = dt(\alpha_{18}') \]
\[ \alpha_{19}'' = dt(\alpha_{19}') \]
\[ \alpha_{24}'' = dt(\alpha_{24}') \]
\[ \alpha_{25}'' = dt(\alpha_{25}') \]
\[ \alpha_{26}'' = dt(\alpha_{26}') \]
\[ \alpha_{27}'' = dt(\alpha_{27}') \]

\%===================================================================
\% Declare value for torque (3rd order, which are edited in Fortran Code)
\% For now, only consider torque generator at trunk rot. about 1st axis
\%===================================================================

\[ \text{TOR}_7 = T^3 \]
\[ \text{TOR}_9 = T^3 \]
\[ \text{TOR}_{11} = T^3 \]
\[ \text{TOR}_{12} = T^3 \]
\[ \text{TOR}_{13} = T^3 \]
\[ \text{TOR}_{28} = T^3 \]

\%===================================================================
\% Input constants, variables, etc. for CODE
\%===================================================================

\text{INPUT} \quad T_{\text{INITIAL}}=2.9, \quad T_{\text{FINAL}}=3.25 \quad \% \text{Begin/end times}
\text{INPUT} \quad T_{\text{INTEGSTP}}=0.0003333, \quad \text{PRINTINT}=10 \quad \% \text{Integration/print step}
\text{INPUT} \quad \text{ABSERR}=1.0E-08, \quad \text{RELERR}=1.0E-07 \quad \% \text{Error tolerances}
\text{INPUT} \quad G=9.81, \quad K_1=1000, \quad K_2=1000, \quad N_{\alpha}= -15.0, \quad N_{\alpha}= -15.0
\text{INPUT} \quad Q_{1}=0.0, \quad Q_{2}=0.0, \quad Q_{3}=0.0, \quad Q_{7}=0.0, \quad Q_{9}=0.0
\text{INPUT} \quad Q_{20}=0.0, \quad Q_{21}=0.0, \quad Q_{22}=0.0
\text{INPUT} \quad Q_{11}=0.0, \quad Q_{12}=0.0, \quad Q_{13}=0.0, \quad Q_{28}=0.0
\text{INPUT} \quad U_{7}=0.0, \quad U_{9}=0.0, \quad U_{11}=0.0, \quad U_{13}=0.0, \quad U_{20}=0.0, \quad U_{21}=0.0, \quad U_{22}=0.0, \quad U_{28}=0.0
INPUT  MA=12.129, MB=37.766, MBH=5.025, MC=15.172, MD=2.518, ME=1.280, MH=0.326, ML=2.413, MM=1.317, MMF=0.374, MJ=0.145
INPUT  LAO=0.096, LA=0.203, LBO=0.235, LB=0.485, LCO=0.091, LC=0.236, LD=0.126, LD=0.287
INPUT  LEO=0.107, LE=0.260, LHO=0.083, LH=0.206, LLO=0.123, LL=0.281, LMO=0.111, LM=0.267
INPUT  IA1=0.082, IA2=0.141, IA3=0.139, IB1=1.340, IB2=1.501, IB3=0.436, IC1=0.068, IC2=0.097, IC3=0.112
INPUT  ID1=0.019, ID2=0.019, ID3=0.003, IE1=0.007, IE2=0.007, IE3=0.001, IH1=0.0015, IH2=0.0014, IH3=0.0002
INPUT  IL1=0.018, IL2=0.018, IL3=0.003, IM1=0.007, IM2=0.007, IM3=0.0010
INPUT  LBHO=0.1221, LBH=0.240, IBH1=0.025, IBH2=0.0257, IBH3=0.0155
INPUT  LMFO=0.079, LMF=0.195, IMF1=0.0014, IMF2=0.0012, IMF3=0.0002
%===================================================================
%       List quantities to be output from FORTRAN code
%===================================================================
OUTPUT  T,Q1,Q2,Q3,TRA1,TRA2,TRA3,ANG4,ANG5,ANG6,ANG7,ANG8,ANG9,NANG,THETA1,THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8,THETA9,THETA10,THETA11,THETA12,THETA13,THETA14,THETA15,THETA16,THETA17,THETA18,THETA19,THETA20,THETA21,THETA22,THETA23,THETA24,THETA25,THETA26,THETA27
OUTPUT  T,TRA1',TRA2',TRA3',ANG4',ANG5',ANG6',U7,ANG8',U9,THETA1',THETA2',U28,U11,U12,U13,ANG14',ANG15',ANG16',ANG17',ANG18',ANG19',U20,U21,U22,ANG24',ANG25',ANG26',ANG27'
OUTPUT  T,POAOX,POAOY,POAOZ,POBOX,POBOY,POBOZ,POBOX,POCOY,POCOZ,POCOZ,PODOY,PODOZ,POEOX,POEOY,POEOZ,POEOX,POEOY,POEOZ,POHOX,POHOY,POHOZ,POLOX,POLOY,POLOY,POLOX,POLOY,POLOY
OUTPUT  T,VOAOX,VOAOY,VOAOZ,VOBOX,VOBOY,VOBOZ,VOBOX,VOCOY,VOCOZ,VOCOZ,VOCHY,VOCHZ,VOCHY,VOCHZ,VOCHY,VOCHZ,VOJOX,VOJOY,VOJOY,VOJOX,VOJOY,VOJOX,VOJOY
OUTPUT  T,KEA,KEB,KEC,KEE,KEH,KEI,KEJ,PEA,PEB,PEC,PEF,PEF,PEH,PEL,PEM,PEJ,TE
% Units for time and angle

UNITS  T=S, \{Q1,Q2,Q3,TRA1,TRA2,TRA3,Q20,Q21,Q22\}=M,
       \{TRA1',TRA2',TRA3',U20,U21,U22\}=M/S

UNITS  \{ANG4,ANG5,ANG6,Q7,ANG8,Q9,THETA1,THETA2,Q28,Q11,Q12,Q13,ANG14,ANG15
       ,ANG16,ANG17,ANG18,ANG19,ANG24,ANG25,ANG26,ANG27\}=DEGS

UNITS  \{ANG4',ANG5',ANG6',U7,ANG8',U9,THETA1',THETA2',U28,U11,U12,U13,ANG14'
       ,ANG15',ANG16',ANG17',ANG18',ANG19',ANG24',ANG25',ANG26',ANG27'\}=RAD/S


UNITS  \{IA1,IA2,IA3,IB1,IB2,IB3,IBH1,IBH2,IBH3,IC1,IC2,IC3,ID1,ID2,ID3,IE1
       ,IE2,IE3,IH1,IH2,IH3,IL1,IL2,IL3,IM1,IM2,IM3,IMF1,IMF2,IMF3\}=KG.M^2

UNITS  \{G=M/S^2, [K1,K2]=N, [NANG,MANG]=DEGS\}

UNITS  \{LA,LAO,LB,LBO,LBH,LC,LCO,LD,LDO,LE,LEO,LH,LHO,LL,LLO,LM,LMF,LMF0\}=M

UNITS  \{VOP1X,VOP1Y,VOP1Z,VOP2X,VOP2Y,VOP2Z,VOP3X,VOP3Y,VOP3Z,VOP4X,VOP4Y
       ,VOP4Z,VOP5X,VOP5Y,VOP5Z,VOP6X,VOP6Y,VOP6Z,VOP7X,VOP7Y,VOP7Z,VOJX,VOJY
       ,VOJZ,VOPX,VOPY,VOPZ,VOPRX,VOPRY,VOPRZ,VOPR10X,VOPR10Y,VOPR11X,VOPR11Y
       ,VOPR11Z\}=M/S

UNITS  \{VOAOX,VOAOY,VOAOZ,VOBOX,VOBOY,VOBOZ,VOCOX,VOCOY,VOCOZ,VODOX,VODOY
       ,VODOZ,VODEX,VODEY,VODEZ,VOHGX,VOHGY,VOHGOZ,VOLOX,VOLOY,VOLOZ,VOMOX,VOM
       OY,VOMOZ\}=M/S

UNITS  \{TOR4,TOR5,TOR6,TOR7,TOR8,TOR9,TOR10,TOR11,TOR12,TOR13,TOR14,TOR15,TOR16
       ,TOR17,TOR18,TOR19,TOR23,TOR24,TOR25,TOR26,TOR27,TOR28\}=N.M

UNITS  \{KEA,KEB,KEC,KED,KEE,KEF,KEG,KEH,KEL,KEM,KJE,KEP,KEQ,KEP,KEQ
       ,KER,KEF,TE\}=KG.M^2/S^2

UNITS  \{RX,RY,RZ,RX1,RY1,RZ1\}=N

% Fortran code generation for numerical solution

code dynamics() torthrow6.for

%---------------------------------------------------------------

194
APPENDIX C

AUTOLEV CODE

Angle-driven model of overarm throwing

%==============================================================================
%                   8-SEGMENT ANGLE-DRIVEN MODEL (23 DOF )
%
% This code is written by Nurhidayah Omar for study on throwing.
%   Modification: 1) trunk + head
%                   2) nonthrowing forearm + hand
%
%==============================================================================
% This model comprises of 23 DOF and eight segments (pelvis, trunk
% plus head, shoulder girdle, throwing arm (upper arm, forearm and
% hand) and non-throwing (upper arm and forearm plus hand).
% 6DOF describing rotation and translation of pelvis about global,
% 3DOF describing rotation of trunk and 3DOF describing
% rotation of shoulder girdle.
% For throwing arm: 3DOF describing rotation of upper arm, 3DOF
% describing rotation of forearm and 2DOF describing rotation of
% hand.
% For non-throwing arm: 3DOF representing rotation of upper arm and
% 1DOF to describe rotation of forearm.
% z-axis (3rd axis) is the vertical axis, y-axis (2nd axis) is the
% horizontal axis towards home-plate (throwing direction) and
% x-axis (1st axis) is the medial/lateral axis.
% Torque at shoulder girdle about 1st axis (TOR10) and torque at
% wrist
% about 3rd axis (TOR19) has been calculated but it is not used in
% the simulation model. The angle, angular velocity and angular
% acceleration of both are also calculated but will set to 0 in
% Fortran.

195
% Newtonian reference frame
NEWTONIAN N

% Simplifies the output equations
AUTOZ on

% Physical declarations: bodies, frames, points and particles

BODIES A, B, BH, C, D, E, H, L, M, MF
POINTS O, P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12, P13
PARTICLES J

MASS A = MA % Mass of pelvis (segment A)
MASS B = MB % Mass of trunk (segment B)
MASS BH = MBH % Mass of head (segment BH)
MASS C = MC % Mass of shoulder girdle (segment C)
MASS D = MD % Mass of upper arm (segment D)
MASS E = ME % Mass of forearm (segment E)
MASS H = MH % Mass of hand (segment F)
MASS L = ML % Mass of free upper arm (segment L)
MASS M = MM % Mass of free forearm (segment M)
MASS MF = MMF % Mass of free hand (segment MF)
MASS J = MJ % Mass of particle (ball)

INERTIA A, IA1, IA2, IA3 % Moment-of-inertia of A
INERTIA B, IB1, IB2, IB3 % Moment-of-inertia of B
INERTIA BH, IBH1, IBH2, IBH3 % Moment-of-inertia of BH
INERTIA C, IC1, IC2, IC3 % Moment-of-inertia of C
INERTIA D, ID1, ID2, ID3 % Moment-of-inertia of D
INERTIA E, IE1, IE2, IE3 % Moment-of-inertia of E
INERTIA H, IH1, IH2, IH3 % Moment-of-inertia of H
INERTIA L, IL1, IL2, IL3 % Moment-of-inertia of L
INERTIA M, IM1, IM2, IM3 % Moment-of-inertia of M
INERTIA MF, IMF1, IMF2, IMF3 % Moment-of-inertia of MF

CONSTANTS G % Gravity
CONSTANTS NANG % Head position
CONSTANTS MANG % Nonthrowing hand position
CONSTANTS K{2} % Constant spring
CONSTANTS LAO, LA % Length of pelvis
CONSTANTS LB0, LB % Length of trunk
CONSTANTS LBHO, LBH % Length of head
CONSTANTS LCO, LC % Length of shoulder girdle
CONSTANTS LDO,LD %Length of throwing upperarm
CONSTANTS LEO,LE %Length of throwing forearm
CONSTANTS LHO,LH %Length of throwing hand
CONSTANTS LLO,LL %Length of nonthrowing upperarm
CONSTANTS LMO,LM %Length of nonthrowing forearm
CONSTANTS LMFO,LMF %Length of nonthrowing hand

% Mathematical declarations: Generalised coordinates and generalised speed

VARIABLES Q1',Q2',Q3' %origin (midpoint pelvis)
VARIABLES Q4',Q5',Q6' %angle and angular speed of pelvis
VARIABLES Q7',Q8',Q9' %angle and angular speed of trunk
VARIABLES Q10',Q23',Q28' %shoulder girdle
VARIABLES Q11',Q12',Q13' %angle and angular speed of shoulder
VARIABLES Q14',Q15',Q16' %angle and angular speed of elbow
VARIABLES Q17',Q18',Q19' %angle and angular speed of wrist
VARIABLES Q20',Q21',Q22' %position of hand
VARIABLES Q24',Q25',Q26' %angle and angular speed of f.shoulder
VARIABLES Q27' %angle and angular speed of f.elbow
VARIABLES U{28}' specified TRA1'' ,TRA2'' ,TRA3''
specified THETA1'' ,THETA2'' ,THETA3''
specified ANG4'' ,ANG5'' ,ANG6''
specified ANG7'' ,ANG8'' ,ANG9''
specified ANG11'' ,ANG12'' ,ANG13''
specified ANG14'' ,ANG15'' ,ANG16''
specified ANG17'' ,ANG18'' ,ANG19''
specified ANG24'' ,ANG25'' ,ANG26''
specified ANG27''

% Declare additional variables

VARIABLES RX,RY,RZ %Force to hold Midpoint pelvis
VARIABLES RX1,RY1,RZ1 %Hand/Particle force

VARIABLES TOR4,TOR5,TOR6,TOR7,TOR8,TOR9,TOR10,TOR11,TOR12,TOR13,TOR14,TOR15,TO R16,TOR17,TOR18,TOR19,TOR23,TOR24,TOR25,TOR26,TOR27,TOR28

ZEE_NOT=[RX,RY,RZ,TOR4,TOR5,TOR6,TOR7,TOR8,TOR9,TOR10,TOR11,TOR12,TOR13,TOR14,TO R15,TOR16,TOR17,TOR18,TOR19,TOR23,TOR24,TOR25,TOR26,TOR27,TOR28]
% Kinematic differential equations

Q1' = U1
Q2' = U2
Q3' = U3
TRA1 = T^3
TRA2 = T^3
TRA3 = T^3
TRA1'' = dt(TRA1')
TRA2'' = dt(TRA2')
TRA3'' = dt(TRA3')
Q20' = U20
Q21' = U21
Q22' = U22

% Position vectors and direction cosine matrices

dircos(N,A,BODY123,ANG4,ANG5,ANG6)
P_O_P1> = Q1*N1> + TRA1*N1> + Q2*N2> + TRA2*N2> + Q3*N3> + TRA3*N3>
P_P1_AO> = LAO*A1> %segment in horizontal position
P_P1_P2> = 0.4*LA*A1> %segment in horizontal position
P_P1_P3> = -0.4*LA*A1>
POP1X = DOT(P_O_P1>,N1>)
POP1Y = DOT(P_O_P1>,N2>)
POP1Z = DOT(P_O_P1>,N3>)
P_O_AO> = P_O_P1> + P_P1_AO>
P_O_P2> = P_O_P1> + P_P1_P2>
P_O_P3> = P_O_P1> + P_P1_P3>
POAOX = DOT(P_O_AO>,N1>)
POAOY = DOT(P_O_AO>,N2>)
POAOZ = DOT(P_O_AO>,N3>)
POP2X = DOT(P_O_P2>,N1>)
POP2Y = DOT(P_O_P2>,N2>)
POP2Z = DOT(P_O_P2>,N3>)
POP3X = DOT(P_O_P3>,N1>)
POP3Y = DOT(P_O_P3>,N2>)
POP3Z = DOT(P_O_P3>,N3>
% Segment 2(B) - trunk + head

\[ \text{dircos}(B,A,BODY321,-ANG9,-ANG8,-ANG7) \]
\[ P_{P1\_BO>} = 1*LBO*B3> \] %segment in vertical position
\[ P_{P1\_P4>} = 1*LB*B3> \] %segment in vertical position
\[ P_{O\_BO>} = P_{O\_P1>} + P_{P1\_BO>} \]
\[ P_{O\_P4>} = P_{O\_P1>} + P_{P1\_P4>} \]
\[ \text{POBOX}=\text{DOT}(P_{O\_BO}>,N1>) \]
\[ \text{POBOY}=\text{DOT}(P_{O\_BO}>,N2>) \]
\[ \text{POBOZ}=\text{DOT}(P_{O\_BO}>,N3>) \]
\[ \text{POP4X}=\text{DOT}(P_{O\_P4}>,N1>) \]
\[ \text{POP4Y}=\text{DOT}(P_{O\_P4}>,N2>) \]
\[ \text{POP4Z}=\text{DOT}(P_{O\_P4}>,N3>) \]

\[ \text{simprot}(B,BH,1,NANG) \]
\[ P_{P4\_BHO>} = LBHO*BH3> \] %position of head
\[ P_{P4\_P12>} = LBH*BH3> \]
\[ P_{O\_BHO>} = P_{O\_P4>} + P_{P4\_BHO>} \]
\[ P_{O\_P12>} = P_{O\_P4>} + P_{P4\_P12>} \]
\[ \text{POBHOX}=\text{DOT}(P_{O\_BHO}>,N1>) \]
\[ \text{POBHOY}=\text{DOT}(P_{O\_BHO}>,N2>) \]
\[ \text{POBHOZ}=\text{DOT}(P_{O\_BHO}>,N3>) \]
\[ \text{POP12X}=\text{DOT}(P_{O\_P12}>,N1>) \]
\[ \text{POP12Y}=\text{DOT}(P_{O\_P12}>,N2>) \]
\[ \text{POP12Z}=\text{DOT}(P_{O\_P12}>,N3>) \]

% Segment 3(C) - shoulder girdle

\[ \text{dircos}(C,B,BODY321,-THETA3,-THETA2,-THETA1) \]
\[ P_{P4\_CO>} = LCO*C1> \]
\[ P_{P4\_P5>} = 0.7*LC*C1> \]
\[ P_{P4\_P6>} = -0.7*LC*C1> \]
\[ P_{O\_CO>} = P_{O\_P4>} + P_{P4\_CO>} \]
\[ P_{O\_P5>} = P_{O\_P4>} + P_{P4\_P5>} \]
\[ P_{O\_P6>} = P_{O\_P4>} + P_{P4\_P6>} \]
\[ \text{POCOX} = \text{DOT}(P_{O\_CO}>,N1>) \]
\[ \text{POCOY} = \text{DOT}(P_{O\_CO}>,N2>) \]
\[ \text{POCOZ} = \text{DOT}(P_{O\_CO}>,N3>) \]
\[ \text{POP5X} = \text{DOT}(P_{O\_P5}>,N1>) \]
POP5Y = DOT(P_O_P5>,N2>)
POP5Z = DOT(P_O_P5>,N3>)
POP6X = DOT(P_O_P6>,N1>)
POP6Y = DOT(P_O_P6>,N2>)
POP6Z = DOT(P_O_P6>,N3>)

%---------------------------------------------------------------------------------------------------
%Segment 4(D) - upper arm (throwing arm)
%---------------------------------------------------------------------------------------------------
dircos(D,C,BODY321,-ANG13,-ANG12,-ANG11)
P_P5_DO> = -1*LDO*D3>
P_P5_P7> = -1*LD*D3>
P_O_DO> = P_O_P5> + P_P5_DO>
P_O_P7> = P_O_P5> + P_P5_P7>
PODOX = DOT(P_O_DO>,N1>)
PODOY = DOT(P_O_DO>,N2>)
PODOZ = DOT(P_O_DO>,N3>)
POP7X = DOT(P_O_P7>,N1>)
POP7Y = DOT(P_O_P7>,N2>)
POP7Z = DOT(P_O_P7>,N3>)

%---------------------------------------------------------------------------------------------------
% Segment 5(E) - forearm (throwing arm)
%---------------------------------------------------------------------------------------------------
dircos(E,D,BODY321,-ANG16,-ANG15,-ANG14)
P_P7 EO> = -1*LEO*E3>
P_P7 P8> = -1.0*LE*E3>
P_O EO> = P_O_P7> + P_P7 EO>
P_O P8> = P_O_P7> + P_P7 P8>
POEOX = DOT(P_O EO>,N1>)
POEOY = DOT(P_O EO>,N2>)
POEOZ = DOT(P_O EO>,N3>)
POP8X = DOT(P_O P8>,N1>)
POP8Y = DOT(P_O P8>,N2>)
POP8Z = DOT(P_O P8>,N3>)

%---------------------------------------------------------------------------------------------------
% Segment 6(H) - hand (throwing arm)
%---------------------------------------------------------------------------------------------------
dircos(H,E,BODY321,-ANG19,-ANG18,-ANG17)
P_P8 HO> = -1*LHO*H3>
P_P8 P9> = -1.0*LH*H3>
P_O HO> = P_O P8> + P_P8 HO>
\begin{verbatim}
P_{O_P9} = P_{O_P8} + P_{P8_P9}
POHOX = DOT( P_{O_HO}, N1 >)
POHOY = DOT( P_{O_HO}, N2 >)
POHOZ = DOT( P_{O_HO}, N3 >)
POP9X = DOT( P_{O_P9}, N1 >)
POP9Y = DOT( P_{O_P9}, N2 >)
POP9Z = DOT( P_{O_P9}, N3 >)

% Position of hand and ball
\end{verbatim}

\begin{verbatim}
P_{P9_J} = Q20*N1 + Q21*N2 + Q22*N3
P_{O_J} = P_{O_P9} + P_{P9_J}
POJX = DOT( P_{O_J}, N1 >)
POJY = DOT( P_{O_J}, N2 >)
POJZ = DOT( P_{O_J}, N3 >)

% Segment 7 (L) - upper arm (free arm)
\end{verbatim}

\begin{verbatim}
dircos( L, C, BODY321, -ANG26, -ANG25, -ANG24)
P_{P6_LO} = -1*LLO*L3
P_{P6_P10} = -1*LL*L3
P_{O_LO} = P_{O_P6} + P_{P6_LO}
P_{O_P10} = P_{O_P6} + P_{P6_P10}
POLOX = DOT( P_{O_LO}, N1 >)
POLOY = DOT( P_{O_LO}, N2 >)
POLOZ = DOT( P_{O_LO}, N3 >)
POP10X = DOT( P_{O_P10}, N1 >)
POP10Y = DOT( P_{O_P10}, N2 >)
POP10Z = DOT( P_{O_P10}, N3 >)

% Segment 9 (M) - forearm + hand (free arm)
\end{verbatim}

\begin{verbatim}
simprot( L, M, 1, ANG27)
P_{P10_MO} = -1*LMO*M3
P_{P10_P11} = -1*LM*M3
P_{O_MO} = P_{O_P10} + P_{P10_MO}
P_{O_P11} = P_{O_P10} + P_{P10_P11}
POMOX = DOT( P_{O_MO}, N1 >)
POMOY = DOT( P_{O_MO}, N2 >)
POMOZ = DOT( P_{O_MO}, N3 >)
\end{verbatim}
\[ \text{POP11X} = \text{DOT}(\text{P}_O\text{P11},N1) \]
\[ \text{POP11Y} = \text{DOT}(\text{P}_O\text{P11},N2) \]
\[ \text{POP11Z} = \text{DOT}(\text{P}_O\text{P11},N3) \]

%-------------------------------------------------------------------------

\text{simprot(M,MF,1,MANG)}
\text{P}_P11\_MFO\_> = -1*\text{LMFO}\*\text{MF3}>
\text{P}_P11\_P13\_> = -1*\text{LMF}\*\text{MF3}>
\text{P}_O\_MFO\_> = \text{P}_O\_P11\_> + \text{P}_P11\_MFO\_>
\text{P}_O\_P13\_> = \text{P}_O\_P11\_> + \text{P}_P11\_P13\_>
\text{POMFOX} = \text{DOT}(\text{P}_O\_MFO\_>,N1)>
\text{POMFOY} = \text{DOT}(\text{P}_O\_MFO\_>,N2)>
\text{POMFOZ} = \text{DOT}(\text{P}_O\_MFO\_>,N3)>
\text{POP13X} = \text{DOT}(\text{P}_O\_P13\_>,N1)>
\text{POP13Y} = \text{DOT}(\text{P}_O\_P13\_>,N2)>
\text{POP13Z} = \text{DOT}(\text{P}_O\_P13\_>,N3)>

%-------------------------------------------------------------------------

\% Linear and Angular velocities
%=================================================================
% Segment 1(A) - pelvis
%
\text{W}_A\_> = (\cos(\text{ANG5})\ast\cos(\text{ANG6})\ast\text{ANG4}'\ast\sin(\text{ANG6})\ast\text{ANG5}')\ast\text{A1} > + \text{U4}\ast\text{A1} > + \(-\cos(\text{ANG5})\ast\sin(\text{ANG6})\ast\text{ANG4}'\ast\cos(\text{ANG6})\ast\text{ANG5}')\ast\text{A2} > + \text{U5}\ast\text{A2} > + \(\sin(\text{ANG5})\ast\text{ANG4}'\ast\text{ANG6}')\ast\text{A3} > + \text{U6}\ast\text{A3} >
\text{V}_O\_> = 0>
\text{V2PTS}(N,A,P1,A0)
\text{V2PTS}(N,A,P1,P2)
\text{V2PTS}(N,A,P1,P3)
\text{VOP1X} = \text{DOT}(\text{V}_P1\_N>,N1)>
\text{VOP1Y} = \text{DOT}(\text{V}_P1\_N>,N2)>
\text{VOP1Z} = \text{DOT}(\text{V}_P1\_N>,N3)>
\text{VOAOX} = \text{DOT}(\text{V}_AO\_N>,N1)>
\text{VOAOY} = \text{DOT}(\text{V}_AO\_N>,N2)>
\text{VOAOZ} = \text{DOT}(\text{V}_AO\_N>,N3)>
\text{VOP2X} = \text{DOT}(\text{V}_P2\_N>,N1)>
\text{VOP2Y} = \text{DOT}(\text{V}_P2\_N>,N2)>
\text{VOP2Z} = \text{DOT}(\text{V}_P2\_N>,N3)>
\text{VOP3X} = \text{DOT}(\text{V}_P3\_N>,N1)>
\text{VOP3Y} = \text{DOT}(\text{V}_P3\_N>,N2)>
\text{VOP3Z} = \text{DOT}(\text{V}_P3\_N>,N3)>

202
% Segment 2(B) - trunk + head

\[ W_{B_A} = (\cos(\text{ANG8}) \cdot \cos(\text{ANG9}) \cdot \text{ANG7}' + \sin(\text{ANG9}) \cdot \text{ANG8}') \cdot B_1> + U_7 \cdot B_1> + (-\cos(\text{ANG8}) \cdot \sin(\text{ANG9}) \cdot \text{ANG7}' + \cos(\text{ANG9}) \cdot \text{ANG8}') \cdot B_2> + U_8 \cdot B_2> + \sin(\text{ANG8}) \cdot \text{ANG7}' + \text{ANG9}') \cdot B_3> + U_9 \cdot B_3> \]

V2PTS(N,B,P1,B0)
V2PTS(N,B,P1,P4)
VOBOX = DOT(V_BO_N>,N1>)
VOBOY = DOT(V_BO_N>,N2>)
VOBOZ = DOT(V_BO_N>,N3>)
VOP4X = DOT(V_P4_N>,N1>)
VOP4Y = DOT(V_P4_N>,N2>)
VOP4Z = DOT(V_P4_N>,N3>)

% Segment 3(C) - shoulder girdle

\[ W_{B_H_B} = 0> \]

V2PTS(N,BH,P4,BHO)
V2PTS(N,BH,P4,P12)

% Segment 4(D) - upper arm (throwing arm)

\[ W_{D_C} = (\cos(\text{ANG12}) \cdot \cos(\text{ANG13}) \cdot \text{ANG11}' + \sin(\text{ANG13}) \cdot \text{ANG12}') \cdot D_1> + U_{11} \cdot D_1> + (-\cos(\text{ANG12}) \cdot \sin(\text{ANG13}) \cdot \text{ANG11}' + \cos(\text{ANG13}) \cdot \text{ANG12}') \cdot D_2> + U_{12} \cdot D_2> + \sin(\text{ANG12}) \cdot \text{ANG11}' + \text{ANG13}') \cdot D_3> + U_{13} \cdot D_3> \]

V2PTS(N,C,P4,C0)
V2PTS(N,C,P4,P5)
V2PTS(N,C,P4,P6)
VOCOX = DOT(V_CO_N>,N1>)
VOCOY = DOT(V_CO_N>,N2>)
VOCOZ = DOT(V_CO_N>,N3>)
VOP5X = DOT(V_P5_N>,N1>)
VOP5Y = DOT(V_P5_N>,N2>)
VOP5Z = DOT(V_P5_N>,N3>)
VOP6X = DOT(V_P6_N>,N1>)
VOP6Y = DOT(V_P6_N>,N2>)
VOP6Z = DOT(V_P6_N>,N3>)

203
V2PTS(N,D,P5,DO)
V2PTS(N,D,P5,F7)
VODOX = DOT(V_DO_N>,N1>)
VODOY = DOT(V_DO_N>,N2>)
VODOZ = DOT(V_DO_N>,N3>)
VOP7X = DOT(V_P7_N>,N1>)
VOP7Y = DOT(V_P7_N>,N2>)
VOP7Z = DOT(V_P7_N>,N3>)
%----------------------------------------------
% Segment 5(E) - forearm (throwing arm)
%-----------------------------------------------------------------------
W_E_D> = (COS(ANG15)*COS(ANG16)*ANG14'+SIN(ANG16)*ANG15')*E1> +
U14*E1> + (-COS(ANG15)*SIN(ANG16)*ANG14'+COS(ANG16)*ANG15')*E2> +
U15*E2> + (SIN(ANG15)*ANG14'+ANG16')*E3> + U16*E3>
V2PTS(N,E,F7,EO)
V2PTS(N,E,P7,F8)
VOEOX = DOT(V_EO_N>,N1>)
VOEOY = DOT(V_EO_N>,N2>)
VOEOZ = DOT(V_EO_N>,N3>)
VOP8X = DOT(V_P8_N>,N1>)
VOP8Y = DOT(V_P8_N>,N2>)
VOP8Z = DOT(V_P8_N>,N3>)
%-----------------------------------------------------------------------
% Segment 6(H) - hand (throwing arm)
%-----------------------------------------------------------------------
W_H_E> = (COS(ANG18)*COS(ANG19)*ANG17'+SIN(ANG19)*ANG18')*H1> +
U17*H1> + (-COS(ANG18)*SIN(ANG19)*ANG17'+COS(ANG19)*ANG18')*H2> +
U18*H2> + (SIN(ANG18)*ANG17'+ANG19')*H3> + U19*H3>
V2PTS(N,H,F8,HO)
V2PTS(N,H,P8,F9)
VOHOX = DOT(V_HO_N>,N1>)
VOHOY = DOT(V_HO_N>,N2>)
VOHOZ = DOT(V_HO_N>,N3>)
VOP9X = DOT(V_P9_N>,N1>)
VOP9Y = DOT(V_P9_N>,N2>)
VOP9Z = DOT(V_P9_N>,N3>)
%-----------------------------------------------------------------------
V_J_N> = DT(P_O_J>,N)
VOJX = DOT(V_J_N>,N1>)
VOJY = DOT(V_J_N>,N2>)
VOJZ = DOT(V_J_N>,N3>)
% Segment 8 (L) - upper arm (free arm)

\[ W_L_C = (\cos(\text{ANG25}) \cdot \cos(\text{ANG26}) \cdot \text{ANG24}' + \sin(\text{ANG26}) \cdot \text{ANG25}') \cdot L1 > + U24 \cdot L1 > + (-\cos(\text{ANG25}) \cdot \sin(\text{ANG26}) \cdot \text{ANG24}' + \cos(\text{ANG26}) \cdot \text{ANG25}') \cdot L2 > + U25 \cdot L2 > + (\sin(\text{ANG25}) \cdot \text{ANG24}' + \text{ANG26}') \cdot L3 > + U26 \cdot L3 > \]

\[ \text{V2PTS}(N,L,P6,LO) \]
\[ \text{V2PTS}(N,L,P6,P10) \]
\[ \text{VOLOX} = \text{DOT}(\text{V_LO_N}>,N1>) \]
\[ \text{VOLOY} = \text{DOT}(\text{V_LO_N}>,N2>) \]
\[ \text{VOLOZ} = \text{DOT}(\text{V_LO_N}>,N3>) \]
\[ \text{VOP10X} = \text{DOT}(\text{V_P10_N}>,N1>) \]
\[ \text{VOP10Y} = \text{DOT}(\text{V_P10_N}>,N2>) \]
\[ \text{VOP10Z} = \text{DOT}(\text{V_P10_N}>,N3>) \]

% Segment 9 (M) - forearm + hand (free arm)

\[ W_M_L = \text{ANG27}' \cdot M1 > + U27 \cdot M1 > \]

\[ \text{V2PTS}(N,M,P10,M0) \]
\[ \text{V2PTS}(N,M,P10,P11) \]
\[ \text{VOMOX} = \text{DOT}(\text{V_MO_N}>,N1>) \]
\[ \text{VOMOY} = \text{DOT}(\text{V_MO_N}>,N2>) \]
\[ \text{VOMOZ} = \text{DOT}(\text{V_MO_N}>,N3>) \]
\[ \text{VOP11X} = \text{DOT}(\text{V_P11_N}>,N1>) \]
\[ \text{VOP11Y} = \text{DOT}(\text{V_P11_N}>,N2>) \]
\[ \text{VOP11Z} = \text{DOT}(\text{V_P11_N}>,N3>) \]

\[ W_{MF_M} = 0 > \]

\[ \text{V2PTS}(N,\text{MF},P11,\text{MFO}) \]
\[ \text{V2PTS}(N,\text{MF},P11,P13) \]

% Impose motion constraints

\[ \text{AUXILIARY}[1]=U1 \]
\[ \text{AUXILIARY}[2]=U2 \]
\[ \text{AUXILIARY}[3]=U3 \]
\[ \text{AUXILIARY}[4]=U4 \]
\[ \text{AUXILIARY}[5]=U5 \]
\[ \text{AUXILIARY}[6]=U6 \]
\[ \text{AUXILIARY}[7]=U7 \]
\[ \text{AUXILIARY}[8]=U8 \]
AUXILIARY[9]=U9
AUXILIARY[10]=U10
AUXILIARY[12]=U12
AUXILIARY[13]=U13
AUXILIARY[14]=U14
AUXILIARY[15]=U15
AUXILIARY[16]=U16
AUXILIARY[17]=U17
AUXILIARY[18]=U18
AUXILIARY[19]=U19
AUXILIARY[20]=U23
AUXILIARY[21]=U24
AUXILIARY[22]=U25
AUXILIARY[23]=U26
AUXILIARY[24]=U27
AUXILIARY[25]=U28
CONSTRAIN(AUXILIARY[U1,U2,U3,U4,U5,U6,U7,U8,U9,U10,U11,U12,U13,U14,U15,U16,U17,U18,U19,U23,U24,U25,U26,U27,U28])

% Linear and Angular accelerations

% Segment 1(A) - pelvis

ALF_A_N> = DT(W_A_N>,A)
A_O_N> = 0>
A2PTS(N,A,P1,AO)
A2PTS(N,A,P1,P2)
A2PTS(N,A,P1,P3)
A_AO_N> = DT(V_AO_N>,N)
A_P2_N> = DT(V_P2_N>,N)

% Segment 2(B) - trunk + head

ALF_B_A> = DT(W_B_A>,B)
A2PTS(N,B,P1,BO)
A2PTS(N,B,P1,P4)
A_BO_N> = DT(V_BO_N>,N)
A_P4_N> = DT(V_P4_N>,N)
ALF_BH_B> = 0>
A2PTS(N,BH,P4,BHO)
A2PTS(N,BH,P4,P12)
%--------------------------------------------------------------------------
%
Segment 3(C) - shoulder girdle
%--------------------------------------------------------------------------
ALF_C_B> = DT(W_C_B>,C)
A2PTS(N,C,P4,CO)
A2PTS(N,C,P4,P5)
A2PTS(N,C,P4,P6)
A_CO_N> = DT(V_CO_N>,N)
A_P5_N> = DT(V_P5_N>,N)
%--------------------------------------------------------------------------
%
Segment 4(D) - upper arm (throwing arm)
%--------------------------------------------------------------------------
ALF_D_C> = DT(W_D_C>,D)
A2PTS(N,D,P5,DO)
A2PTS(N,D,P5,P7)
A_DO_N> = DT(V_DO_N>,N)
A_P7_N> = DT(V_P7_N>,N)
%--------------------------------------------------------------------------
%
Segment 5(E) - forearm (throwing arm)
%--------------------------------------------------------------------------
ALF_E_D> = DT(W_E_D>,E)
A2PTS(N,E,P7,EO)
A2PTS(N,E,P7,P8)
A_EO_N> = DT(V_EO_N>,N)
A_P8_N> = DT(V_P8_N>,N)
%--------------------------------------------------------------------------
%
Segment 6(H) - hand (throwing arm) & ball
%--------------------------------------------------------------------------
ALF_H_E> = DT(W_H_E>,H)
A2PTS(N,H,P8,HO)
A2PTS(N,H,P8,P9)
A_HO_N> = DT(V_HO_N>,N)
A_P9_N> = DT(V_P9_N>,N)
%--------------------------------------------------------------------------
A_J_N> = DT(V_J_N>,N)
% Segment 8 (L) - upper arm (free arm)

ALF_L_C> = DT(W_L_C>,L)
A2PTS(N,L,P6,LO)
A2PTS(N,L,P6,P10)
A_LO_N> = DT(V_LO_N>,N)
A_P10_N> = DT(V_P10_N>,N)

% Segment 9 (M) - forearm plus hand (free arm)

ALF_M_L> = DT(W_M_L>,M)
A2PTS(N,M,P10,MO)
A2PTS(N,M,P10,P11)
A_MO_N> = DT(V_MO_N>,N)
A_P11_N> = DT(V_P11_N>,N)

% Kinetic and Potential Energy for every segment

KEA=KE(A)
KEB=KE(B)
KEC=KE(C)
KED=KE(D)
KEE=KE(E)
KEH=KE(H)
KEI=KE(L)
KEM=KE(M)
KEJ=KE(J)

PEA=-1*MA*G*POAOZ
PEB=-1*MB*G*POBOZ
PEC=-1*MC*G*POCOZ
PED=-1*MD*G*PODOZ
PEE=-1*ME*G*POEOZ
PEH=-1*MH*G*POHOZ
PEI=-1*ML*G*POLOZ
PEM = -1*MM*G*POMOZ
PEJ = -1*MJ*G*POJZ

% Expressions for forces and torques

% For ball release

STRETCH1 = DOT(P_P9_J>, N1>)
STRETCH2 = DOT(P_P9_J>, N2>)
STRETCH3 = DOT(P_P9_J>, N3>)
VELOCITY1 = DT(STRETCH1)
VELOCITY2 = DT(STRETCH2)
VELOCITY3 = DT(STRETCH3)
RX1 = (-K1*STRETCH1 - K2*VELOCITY1)
RY1 = (-K1*STRETCH2 - K2*VELOCITY2)
RZ1 = (-K1*STRETCH3 - K2*VELOCITY3)

%-------------------------------------------------
GRAVITY(G*N3>)
FORCE(P1,RX*N1> + RY*N2> + RZ*N3>)
FORCE(P9/J,RX1*N1> + RY1*N2> + RZ1*N3>)

%------------------------------------
% Equations of motion
%-------------------------------------------------
ZERO = FR() + FRSTAR()
KANE(RX,RY,RZ,TOR4,TOR5,TOR6,TOR7,TOR8,TOR9,TOR10,TOR11,TOR12,TOR13,
TOR14,TOR15,TOR16,TOR17,TOR18,TOR19,TOR23,TOR24,TOR25,TOR26,TOR27,TO
R28)

%------------------------------------

% Declare value for Theta, Phi and angle joints (3rd order, which
% are edited in Fortran Code)

THETA1 = T^3
THETA2 = T^3
THETA3 = T^3
ANG4 = T^3
ANG5 = T^3
ANG6 = T^3
ANG7 = T^3
ANG8 = T^3
ANG9 = T^3
ANG11 = T^3
ANG12 = T^3
ANG13 = T^3
ANG14 = T^3
ANG15 = T^3
ANG16 = T^3
ANG17 = T^3
ANG18 = T^3
ANG19 = T^3
ANG24 = T^3
ANG25 = T^3
ANG26 = T^3
ANG27 = T^3

%-------------------------------------------------
\[ THETA_1'' = dt(THETA_1') \]
\[ THETA_2'' = dt(THETA_2') \]
\[ THETA_3'' = dt(THETA_3') \]
\[ ANG_4'' = dt(ANG_4') \]
\[ ANG_5'' = dt(ANG_5') \]
\[ ANG_6'' = dt(ANG_6') \]
\[ ANG_7'' = dt(ANG_7') \]
\[ ANG_8'' = dt(ANG_8') \]
\[ ANG_9'' = dt(ANG_9') \]
\[ ANG_{11}'' = dt(ANG_{11}') \]
\[ ANG_{12}'' = dt(ANG_{12}') \]
\[ ANG_{13}'' = dt(ANG_{13}') \]
\[ ANG_{14}'' = dt(ANG_{14}') \]
\[ ANG_{15}'' = dt(ANG_{15}') \]
\[ ANG_{16}'' = dt(ANG_{16}') \]
\[ ANG_{17}'' = dt(ANG_{17}') \]
\[ ANG_{18}'' = dt(ANG_{18}') \]
\[ ANG_{19}'' = dt(ANG_{19}') \]
\[ ANG_{24}'' = dt(ANG_{24}') \]
\[ ANG_{25}'' = dt(ANG_{25}') \]
\[ ANG_{26}'' = dt(ANG_{26}') \]
\[ ANG_{27}'' = dt(ANG_{27}') \]

%-------------------------------------------------------------
% Input constants, variables, etc. for CODE
%-------------------------------------------------------------

INPUT TINITIAL=3.77, TFINAL=4.07  %Begin/end times
INPUT INTEGRSTP=0.0003333, PRINTINT=10  %Integration/print step
INPUT ABSERR=1.0E-08, RELERR=1.0E-07  %Error tolerances
INPUT G=-9.81, K1=1000, K2=1000, NANG= -15.0, MANG= -15.0
INPUT Q1=0.0, Q2=0.0, Q3=0.0, Q20=0.0, Q21=0.0, Q22=0.0
INPUT U20=0.0, U21=0.0, U22=0.0
INPUT MA=12.129, MB=37.766, MBH=5.025, MC=15.172, MD=2.518,
    ME=1.280, MH=0.326, ML=2.413, MM=1.317, MMF=0.374, MJ=0.145
INPUT LAO=0.096, LA=0.203, LBO=0.235, LB=0.485, LCO=0.091,
    LC=0.236, LDO=0.126, LD=0.287
INPUT LEO=0.107, LE=0.260, LHO=0.0832, LH=0.2060, LLO=0.123,
    LL=0.281, LMO=0.111, LM=0.267
INPUT IA1=0.082, IA2=0.141, IA3=0.139, IB1=1.340, IB2=1.501,
    IB3=0.436, IC1=0.068, IC2=0.097, IC3=0.112
INPUT ID1=0.019, ID2=0.019, ID3=0.003, IE1=0.007, IE2=0.007,
    IE3=0.001, IH1=0.0015, IH2=0.0014, IH3=0.0002
INPUT  IL1=0.018, IL2=0.018, IL3=0.003, IM1=0.007, IM2=0.007, IM3=0.0010
INPUT  LBHO=0.1221, LBH=0.2400, IBH1=0.0257, IBH2=0.0257, IBH3=0.0155
INPUT  LMFO=0.079, LMF=0.195, IMF1=0.0014, IMF2=0.0012, IMF3=0.0002

%====================================
%       List quantities to be output from FORTRAN code
%====================================

OUTPUT T, Q1, Q2, Q3, TRA1, TRA2, TRA3, ANG4, ANG5, ANG6, ANG7, ANG8, ANG9, NANG, THETA1, THETA2, THETA3, ANG11, ANG12, ANG13, ANG14, ANG15, ANG16, ANG17, ANG18, ANG19, Q20, Q21, Q22, ANG24, ANG25, ANG26, ANG27


OUTPUT T, POAOX, POAOY, POAOZ, POBOX, POBOY, POBOZ, POCOX, POCOY, POCOZ, PODOX, PODOY, PODOZ, POEOX, POEOY, POEOZ, POHOX, POHOY, POHOZ, POLOX, POLOY, POLOZ, POMOX, POMOZ


OUTPUT T, VOAOX, VOAOY, VOAOZ, VOBOX, VOBOY, VOBOZ, VOCOX, VOCOY, VOCOZ, VODOX, VODOY, VODOZ, VOEOX, VOEOY, VOEOZ, VOHOX, VOHOY, VOHOZ, VOLOX, VOLOY, VOLOZ, VOMOX, VOMOZ

OUTPUT T, TOR4, TOR5, TOR6, TOR7, TOR8, TOR9, TOR10, TOR11, TOR12, TOR13, TOR14, TOR15, TOR16, TOR17, TOR18, TOR19, TOR24, TOR25, TOR26, TOR27

OUTPUT T, RX, RY, RZ, RX1, RY1, RZ1

OUTPUT T, KEA, KEB, KEC, KEK, KEH, KEL, KEM, KEJ, PEA, PEB, PEC, PED, PEE, PEH, PEL, PEM, PEJ, TE

% Units for time and angle

UNITS T=S, [Q1, Q2, Q3, TRA1, TRA2, TRA3, Q20, Q21, Q22]=M,
[TRA1', TRA2', TRA3', U20, U21, U22]=M/S

UNITS [ANG4, ANG5, ANG6, ANG7, ANG8, ANG9, THETA1, THETA2, THETA3, ANG11, ANG12, ANG13, ANG14, ANG15, ANG16, ANG17, ANG18, ANG19, ANG24, ANG25, ANG26, ANG27]=DEGS
UNITS

UNITS

UNITS
[IA1, IA2, IA3, IB1, IB2, IB3, IBH1, IBH2, IBH3, IC1, IC2, IC3, ID1, ID2, ID3, IE1, IE2, IE3, IH1, IH2, IH3, IL1, IL2, IL3, IM1, IM2, IM3, IMF1, IMF2, IMF3] = KG.M^2

UNITS
G = M/S^2, [K1, K2] = N, [NANG, MANG] = DEGS

UNITS

UNITS

UNITS

UNITS
[VOAOX, VOAOY, VOAOZ, VOBOX, VOBOY, VOBOZ, VOCOX, VOCOY, VOCOZ, VODOX, VODOY, V ODZ, VEOOX, VEOOY, VEOOZ, VOHOX, VOHOY, VOHOZ, VOLOX, VOLOY, VOLOZ, VOMOX, VOM OY, VOMOZ] = M/S

UNITS
[TOR4, TOR5, TOR6, TOR7, TOR8, TOR9, TOR10, TOR11, TOR12, TOR13, TOR14, TOR15, TOR16, TOR17, TOR18, TOR19, TOR20, TOR21, TOR22, TOR23, TOR24, TOR25, TOR26, TOR27, TOR28] = N.M

UNITS
[KEA, KEB, KEC, KED, KEE, KEH, KEL, KEJ, PEA, PEB, PEC, PED, PEE, PEH, PEL, PEM , PEJ, TE] = KG.M^2/S^2

UNITS
[RX, RY, RZ, RX1, RY1, RZ1] = N

% Fortran code generation for numerical solution

%--------------------------------------------------------------
% Fortran code generation for numerical solution
%--------------------------------------------------------------
% code dynamics() throwtrans.for
%--------------------------------------------------------------
# APPENDIX D

## ANTHROPOMETRIC MEASUREMENTS FOR SEGMENTAL INERTIA PARAMETERS

All measurements in millimetres.

### Torso

<table>
<thead>
<tr>
<th>Level</th>
<th>Hip</th>
<th>Umbilicus</th>
<th>Ribcage</th>
<th>Nipple</th>
<th>Shoulder</th>
<th>Neck</th>
<th>Nose</th>
<th>Ear</th>
<th>Top</th>
</tr>
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<tr>
<td>Perimeter</td>
<td>1012</td>
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<td>965</td>
<td>372</td>
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<tr>
<td>Width</td>
<td>366</td>
<td>345</td>
<td>302</td>
<td>340</td>
<td>369</td>
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### Left Arm

<table>
<thead>
<tr>
<th>Level</th>
<th>Shoulder</th>
<th>Midarm</th>
<th>Elbow</th>
<th>Forearm</th>
<th>Wrist</th>
<th>Thumb</th>
<th>Knuckle</th>
<th>Nails</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td>548</td>
<td>0</td>
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<tr>
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### Right Arm

<table>
<thead>
<tr>
<th>Level</th>
<th>Shoulder</th>
<th>Midarm</th>
<th>Elbow</th>
<th>Forearm</th>
<th>Wrist</th>
<th>Thumb</th>
<th>Knuckle</th>
<th>Nails</th>
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</tr>
<tr>
<td>Width</td>
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<td></td>
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</tbody>
</table>

### Left Leg

<table>
<thead>
<tr>
<th>Level</th>
<th>Hip</th>
<th>Crotch</th>
<th>Midthigh</th>
<th>Knee</th>
<th>Calf</th>
<th>Ankle</th>
<th>Heel</th>
<th>Arch</th>
<th>Ball</th>
<th>Nails</th>
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</tr>
<tr>
<td>Perimeter</td>
<td>623</td>
<td>561</td>
<td>386</td>
<td>390</td>
<td>230</td>
<td></td>
<td>327</td>
<td></td>
<td>236</td>
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</tr>
<tr>
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</tr>
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<td>Depth</td>
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</table>

### Right Leg

<table>
<thead>
<tr>
<th>Level</th>
<th>Hip</th>
<th>Crotch</th>
<th>Midthigh</th>
<th>Knee</th>
<th>Calf</th>
<th>Ankle</th>
<th>Heel</th>
<th>Arch</th>
<th>Ball</th>
<th>Nails</th>
</tr>
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<tbody>
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<td>920</td>
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<td>215</td>
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<tr>
<td>Perimeter</td>
<td>623</td>
<td>561</td>
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<td>390</td>
<td>230</td>
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<td>327</td>
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<td>236</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Depth</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TOTAL MASS = 89.80 KG   DENSITY = 1.037   HEIGHT: 1.89 m
APPENDIX E

ANATOMICAL POSITION AND AXES OF MOVEMENT

Figure E1: The anatomical position, where the angle of each joint is defined as (0,0,0).

Figure E2: Angle ranges for the (A) trunk and pelvis, (B) upper arm, (C) forearm and (D) hand.
Figure E3: Movement in the sagittal plane (rotation about x-axis).
Figure E4: Movement in the frontal plane (rotation about y-axis).
Figure E5: Movement in the transverse plane (rotation about z-axis).
APPENDIX F

EVALUATION OF ANGLE-DRIVEN MODEL

Example of the displacements and linear velocities of distal segments obtained from the simulation model and performance data (Trial 10 and Trial 13).

**Figure F1**: Displacement (left) and linear velocity (right) of midpelvis of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F2: Displacement (left) and linear velocity (right) of right pelvis of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F3: Displacement (left) and linear velocity (right) of left pelvis of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F4: Displacement (left) and linear velocity (right) of suprasternal of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F5: Displacement (left) and linear velocity (right) of right shoulder of Trial 10: simulation model (solid line) and experiment (dotted line).
**Figure F6:** Displacement (left) and linear velocity (right) of right elbow of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F7: Displacement (left) and linear velocity (right) of right wrist of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F8: Displacement (left) and linear velocity (right) of the ball of Trial 10: simulation model (solid line) and experiment (dotted line).
Figure F9: Displacement (left) and linear velocity (right) of mid-pelvis of Trial 13: simulation model (solid line) and experiment (dotted line).
Figure F10: Displacement (left) and linear velocity (right) of right pelvis of Trial 13: simulation model (solid line) and experiment (dotted line).
Figure F11: Displacement (left) and linear velocity (right) of left pelvis of Trial 13: simulation model (solid line) and experiment (dotted line).
**Figure F12**: Displacement (left) and linear velocity (right) of suprasternal of Trial 13: simulation model (solid line) and experiment (dotted line).
Figure F13: Displacement (left) and linear velocity (right) of right shoulder of Trial 13: simulation model (solid line) and experiment (dotted line).
Figure F14: Displacement (left) and linear velocity (right) of right elbow of Trial 13: simulation model (solid line) and experiment (dotted line).
Figure F15: Displacement (left) and linear velocity (right) of right wrist of Trial 13: simulation model (solid line) and experiment (dotted line).
**Figure F16**: Displacement (left) and linear velocity (right) of the ball of Trial 13: simulation model (solid line) and experiment (dotted line).
APPENDIX G

TORQUE PARAMETER VALUES FROM PREVIOUS STUDIES

Torque parameters (seven parameters) values obtained from previous studies for used as an initial estimated in torque-driven simulation model.

Table G1: Seven parameter values for upper trunk flexion obtained from previous studies

<table>
<thead>
<tr>
<th>Study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Current</th>
<th>Current Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sport</td>
<td>Cricket</td>
<td>Jumping</td>
<td>Triple jump</td>
<td>Jumping</td>
<td>Gymnastic</td>
<td>Tennis</td>
<td>Baseball</td>
<td>Baseball</td>
</tr>
<tr>
<td>Weight</td>
<td>85</td>
<td>72.6</td>
<td>79.2</td>
<td>69.9</td>
<td>89.8</td>
<td>89.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>1.94</td>
<td>1.82</td>
<td>1.74</td>
<td>1.732</td>
<td>1.894</td>
<td>1.894</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmax</td>
<td>240.00</td>
<td>433.00</td>
<td>269.00</td>
<td>199.00</td>
<td>235.00</td>
<td>275.20</td>
<td>409.0</td>
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</tr>
<tr>
<td>To</td>
<td>172.00</td>
<td>289.00</td>
<td>207.00</td>
<td>142.00</td>
<td>168.00</td>
<td>195.60</td>
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<td></td>
</tr>
<tr>
<td>Wmax</td>
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<td>24.90</td>
<td>28.00</td>
<td>9.33</td>
<td>9.18</td>
<td>21.16</td>
<td>6.34</td>
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<tr>
<td>Wc</td>
<td>7.83</td>
<td>14.00</td>
<td>4.20</td>
<td>3.89</td>
<td>4.59</td>
<td>6.90</td>
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<tr>
<td>Amin</td>
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<td>0.69</td>
<td>0.75</td>
<td>0.87</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
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</tr>
<tr>
<td>m</td>
<td>0.15</td>
<td>5.02</td>
<td>0.26</td>
<td>0.13</td>
<td>0.13</td>
<td>1.14</td>
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</tr>
<tr>
<td>w1</td>
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<td>6.00</td>
<td>0.06</td>
<td>1.57</td>
<td>-0.10</td>
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<tr>
<td>wRMS</td>
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<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>wRMS %Tm</td>
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<td>1.30</td>
<td>1.40</td>
<td>1.40</td>
<td>1.41</td>
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</tr>
<tr>
<td>Tmax/To</td>
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<td>0.56</td>
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<td>0.42</td>
<td>0.50</td>
<td>0.33</td>
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</tr>
</tbody>
</table>

Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G2: Seven parameter values for upper trunk extension obtained from previous studies

<table>
<thead>
<tr>
<th>Study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Current Sport</th>
<th>Current Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>85</td>
<td>72.6</td>
<td>79.2</td>
<td>69.9</td>
<td>89.8</td>
<td>89.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>1.94</td>
<td>1.82</td>
<td>1.74</td>
<td>1.732</td>
<td>1.894</td>
<td>1.894</td>
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<td></td>
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<tr>
<td>To</td>
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<td>0.02</td>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

Table G3: Seven parameter values for upper trunk external rotation obtained from previous studies

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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G4: Seven parameter values for upper trunk internal rotation obtained from previous studies

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<td>Jumping</td>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

Table G5: Seven parameter values for scapula external rotation obtained from previous studies

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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G6: Seven parameter values for scapula internal rotation obtained from previous studies

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<td>Triple jump</td>
<td>Jumping</td>
<td>Gymnastic</td>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

Table G7: Seven parameter values for upper arm flexion obtained from previous studies

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<th>D</th>
<th>E</th>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G8: Seven parameter values for upper arm extension obtained from previous studies

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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

Table G9: Seven parameter values for upper arm adduction obtained from previous studies

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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G10: Seven parameter values for upper arm abduction obtained from previous studies

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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

Table G11: Seven parameter values for upper arm internal rotation obtained from previous studies

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<th>F</th>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
**Table G12:** Seven parameter values for upper arm external rotation obtained from previous studies

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wRMS
wRMS %Tm
Tmax/To
Wc/Wmax

Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

**Table G13:** Seven parameter values for forearm flexion obtained from previous studies

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wRMS
wRMS %Tm
Tmax/To
Wc/Wmax

Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
**Table G14**: Seven parameter values for forearm extension obtained from previous studies

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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).

**Table G15**: Seven parameter values for forearm pronation obtained from previous studies

<table>
<thead>
<tr>
<th>Study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Current Study</th>
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<tbody>
<tr>
<td>Sport</td>
<td>Cricket</td>
<td>Jumping</td>
<td>Triple jump</td>
<td>Jumping</td>
<td>Gymnastic</td>
<td>Tennis</td>
<td>Baseball</td>
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<td>72.6</td>
<td>79.2</td>
<td>69.9</td>
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<td>Tmax/To</td>
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Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Table G16: Seven parameter values for forearm supination obtained from previous studies

<table>
<thead>
<tr>
<th>Study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Current Sport</th>
<th>Current Study</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Weight</td>
<td>Height</td>
<td>Tmax</td>
<td>To</td>
<td>Wmax</td>
<td>Wc</td>
<td>Amin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cricket</td>
<td>Jumping</td>
<td>Triple</td>
<td>Jumping</td>
<td>Gymnastic</td>
<td>Tennis</td>
<td>Baseball</td>
<td>Baseball</td>
</tr>
<tr>
<td></td>
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<td>1.94</td>
<td>25.62</td>
<td>18.30</td>
<td>35.35</td>
<td>16.90</td>
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<td>18.30</td>
<td>35.35</td>
<td>16.90</td>
<td>0.86</td>
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<td>0.09</td>
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</table>

Where (Study A: Felton, 2015; Study B: Wilson, 2003; Study C: Allen, 2010; Study D: Lewis, 2011; Study E: Jackson, 2010; Study F: Kentel, 2009).
Description of marker placement for overarm throwing data collection:

**Table H1**: Description of marker placement for data collection

<table>
<thead>
<tr>
<th>Marker</th>
<th>Body Segment</th>
<th>Marker Label(s)</th>
<th>Marker position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>Legs</td>
<td>RTOE, LTOE</td>
<td>Centre line of foot. Centre of marker is 3cm from tip of big toe.</td>
</tr>
<tr>
<td>3,4</td>
<td></td>
<td>RANKM, LANKM</td>
<td>Medial side of ankle bone. The line joining the centres of the 2 ankle markers should define the ankle flexion axis.</td>
</tr>
<tr>
<td>5,6</td>
<td></td>
<td>RANKL, LANKL</td>
<td>Lateral side of ankle bone.</td>
</tr>
<tr>
<td>7,8</td>
<td></td>
<td>RMTPL, LMTPL</td>
<td>Lateral metatarsophalangeal – little toe - joint. The line joining the two MTP markers should define the MTP flexion axis.</td>
</tr>
<tr>
<td>9,10</td>
<td></td>
<td>RMTPM, LMTPM</td>
<td>Medial metatarsophalangeal – big toe – joint.</td>
</tr>
<tr>
<td>11,12</td>
<td></td>
<td>RHEE, LHEE</td>
<td>Centre line of foot, placed on back of heel of shoe.</td>
</tr>
<tr>
<td>13,14</td>
<td></td>
<td>RKNEM, LKNEM</td>
<td>Medial side of knee, the line joining the centres of the 2 knee markers should define the knee flexion axis.</td>
</tr>
<tr>
<td>15,16</td>
<td>RKNEL, LKNEM</td>
<td>Lateral side of knee.</td>
<td></td>
</tr>
<tr>
<td>17,18</td>
<td>Pelvis</td>
<td>RASI, LASI</td>
<td>Bony protrusion of the right and left anterior super iliac.</td>
</tr>
<tr>
<td>19,20</td>
<td>RPSI, LPSI</td>
<td>Dimple created by the right and left posterior suprailiac.</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Thorax</td>
<td>LUM1</td>
<td>First lumbar vertebra.</td>
</tr>
<tr>
<td>22</td>
<td>T10</td>
<td>Tenth thoracic vertebra.</td>
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</tr>
<tr>
<td>23</td>
<td>STRN</td>
<td>Sternum.</td>
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</tr>
<tr>
<td>24</td>
<td>CLAV</td>
<td>Clavicle.</td>
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</tr>
<tr>
<td>25</td>
<td>C7</td>
<td>Seventh cervical vertebra.</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>BAK</td>
<td>Position not crucial. Somewhere in the centre of the right scapula.</td>
<td></td>
</tr>
<tr>
<td>27,28</td>
<td>Arms</td>
<td>RSHOP, LSHOP</td>
<td>Posterior of shoulder.</td>
</tr>
<tr>
<td>29,30</td>
<td>RSHOA, LSHOA</td>
<td>Anterior of shoulder.</td>
<td></td>
</tr>
<tr>
<td>31,32</td>
<td>RSHOT, LSHOT</td>
<td>Top of shoulder.</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>LARM</td>
<td>Somewhere in the centre of the left upper arm. Probably positioned to define the non-throwing arm.</td>
<td></td>
</tr>
<tr>
<td>34,35</td>
<td>RELBM, LELBM</td>
<td>Medial side of elbow. Line joining centre of elbow marker should define flexion axis of the elbow (particularly when reasonably straight). Probably positioned on bony protrusion.</td>
<td></td>
</tr>
<tr>
<td>36,37</td>
<td>RELBL, LELBL</td>
<td>Lateral side of elbow. Probably positioned on anterior side of bony protrusion.</td>
<td></td>
</tr>
</tbody>
</table>
| 38,39 | RWRA, LWRA | Thumb side of wrist. The
centre of the 2 wrist markers should define the flexion axis of the wrist. Marker should be placed on the side of the wrist.

| 40,41 | RWRB, LWRB | Little finger side of wrist. Again the marker should be placed on the side of the wrist. |
| 42,43 | RHAND, LHAND | The marker placed at the centre of metacarpal bones. |
| 44 | Head | RFHD | Right temple. |
| 45 | LFHD | Left temple. |
| 46 | RBHD | Back right of head. |
| 47 | LBHD | Back left of head. |