Force plate analyses of human jumping

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FORCE PLATE ANALYSES OF HUMAN JUMPING

by

DAVID GEORGE KERWIN

A Doctoral Thesis

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

February 1997

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ABSTRACT

Force Plate Analyses of Human Jumping
D.G.Kerwin, Loughborough University, 1997

Conflicts in published research raised a series of questions on the precision of the measurements used to differentiate between vertical jumps performed with and without pre-stretch. Procedures outlined by previous researchers (eg. Komi and Bosco, 1978a; Bedi et al.,1987) were repeated and extended. Force plate data were collected for a series of squat, counter movement and rebound jumps. Individual subjects responded differently and no evidence could be found for an optimal rebound dropping height.

Modal analysis of the force plate highlighted the need for improving its mounting. A frame was designed to raise the resonant frequency of the plate and static and dynamic calibrations revealed point of force application errors. 16 mm cinefilm was selected in preference to video for the subsequent inverse dynamics analysis of rebound jumping.

French physiologist, Marey, observed that people appeared to jump higher following a rebound than a counter movement. A 'Marey' style jumping exercise was used to examine different takeoff and landing strategies. Variations in kinematic data filtering, body segment inertia parameters and quasi-static analysis techniques on the resultant moment moments were investigated. No differences in maximum jump height were found between counter movement and rebound jump takeoffs. This apparent contraction to the findings in previous research was accounted for by variations in the subjects' stretch heights at takeoff. A general proximal to distal sequencing of muscle moment peaking was observed in both takeoff actions, but moments peaked later in rebound takeoffs than when following counter movements. Larger peak moments occurred during landings preceding coming to rest than during the landing phase of the rebound jump. Quasi-statically determined muscle moments about the ankles and knees matched closely with the inverse dynamics values, but joint and overall support moments were consistently over estimated. Conflicts with selected published research findings were shown to arise from a lack of measurement precision. Takeoff velocities were greater following counter movements, but were insufficient to differentiate between jumping techniques. Rebounding was found to increase leg extension.

Improvements in automatic measurement procedures combined with an enhanced understanding of musculo-skeletal modelling were seen as a way of improving future knowledge of neuro-muscular coordination and power production in jumping.
PUBLICATIONS

Aspects of this work have been published as follows:

Books and Journals


Published Abstracts


Conference presentations


Conference presentations/contd


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I wish to express my thanks to:

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and

Mr Darren Atkin, Department of Physical Education, Sports Science and
Recreation Management
for technical assistance and support with the film data collection and processing
and
the subjects who gave freely of their time during data collection.
DEDICATION

To Linda, Tom and Sam
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<tr>
<td>a</td>
<td>acceleration</td>
</tr>
<tr>
<td>AHID</td>
<td>adjusted half visual image data</td>
</tr>
<tr>
<td>ANOVAR1</td>
<td>one way analysis of variance with repeated measures</td>
</tr>
<tr>
<td>AVOVAR2</td>
<td>two way analysis of variance with repeated measures</td>
</tr>
<tr>
<td>$a_x$</td>
<td>point of force application in the x direction on the force plate</td>
</tr>
<tr>
<td>$a_y$</td>
<td>point of force application in the y direction on the force plate</td>
</tr>
<tr>
<td>$a_z$</td>
<td>point of force application in the z direction on the force plate</td>
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<tr>
<td>BW</td>
<td>body weight</td>
</tr>
<tr>
<td>C9</td>
<td>central nine points on force plate surface</td>
</tr>
<tr>
<td>COP</td>
<td>force plate centre of pressure</td>
</tr>
<tr>
<td>CDH</td>
<td>calculated drop height</td>
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<td>CM</td>
<td>mass centre</td>
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<td>CMJ</td>
<td>counter movement jump</td>
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<td>CMJ_t</td>
<td>CMJ takeoff velocity calculated from flight time</td>
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<td>CMJ takeoff velocity calculated by integration</td>
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<tr>
<td>CMJ_{ic}</td>
<td>CMJ takeoff velocity calculated by integration with correction</td>
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<td>CZP</td>
<td>central zone points on force plate surface</td>
</tr>
<tr>
<td>D9</td>
<td>distributed nine points on force plate surface</td>
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<td>DJ15-DJ90</td>
<td>drop jump from 0.15 m to 0.90 m</td>
</tr>
<tr>
<td>DJH</td>
<td>drop jump from high platform</td>
</tr>
<tr>
<td>DJL</td>
<td>drop jump from low platform</td>
</tr>
<tr>
<td>DJM</td>
<td>drop jump from medium height platform</td>
</tr>
<tr>
<td>$\delta \theta$</td>
<td>rotation correction of projected film image data</td>
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<tr>
<td>$\delta t$</td>
<td>small time interval</td>
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<tr>
<td>$d_y_p$</td>
<td>horizontal moment arm from the CM to segment proximal (p) end</td>
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<tr>
<td>$d_z_p$</td>
<td>vertical moment arm from the CM to segment proximal (p) end</td>
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<tr>
<td>$d_y_d$</td>
<td>horizontal moment arm from the CM to segment distal (d) end</td>
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<tr>
<td>$d_z_d$</td>
<td>vertical moment arm from the CM to segment distal (d) end</td>
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<td>$d_y_{d(0)}$</td>
<td>horizontal moment arm from feet CM to force plate COP</td>
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<td>$d_z_{d(0)}$</td>
<td>vertical moment arm from feet CM to force plate COP</td>
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<td>ECP</td>
<td>extreme corner points on force plate surface</td>
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<td>$E_{mm}$</td>
<td>muscle moment energy</td>
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<td>$F_1$</td>
<td>flight phase 1</td>
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<tr>
<td>$F_2$</td>
<td>flight phase 2</td>
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<tr>
<td>F16</td>
<td>cinefilm image data recorded with 16 mm lens</td>
</tr>
<tr>
<td>FAH</td>
<td>forearm and hand segment</td>
</tr>
<tr>
<td>$f_c$</td>
<td>cutoff frequency</td>
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<tr>
<td>$f_r$</td>
<td>natural rocking frequency</td>
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<td>sampling frequency</td>
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<td>$F_y$</td>
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<tr>
<td>$F_z$</td>
<td>vertical force</td>
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<tr>
<td>FZ</td>
<td>cinefilm image data recorded with zoom lens</td>
</tr>
<tr>
<td>g</td>
<td>gravitational acceleration (-9.81 m.s^{-2})</td>
</tr>
<tr>
<td>GCVQS</td>
<td>generalised cross validated quintic spline</td>
</tr>
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</table>
GRI  ground reaction impulse
GST  ground support time
HAT  head, arms and trunk segment
HID  half image data set
HNT  head, neck and trunk segment
ICD  independent central data
IDA  inverse dynamic analysis
Ix   moment of inertia about x axis
Iy   moment of inertia about y axis
Iz   moment of inertia about z axis
JH   jump height
k    spring stiffness
kc   segment CM to radius of gyration as a ratio of segment length
Kc   segment CM to radius of gyration (m)
L1   Heel to Tip of Great Toe
L2   Heel to Metatarsal-Phalangeal
L3   Heel to Lateral Maleolus
L4   Lateral Maleolus to Metatarsal-Phalangeal
L5   Lateral Maleolus to lateral epicondyle
L6   Lateral epicondyle to femoral epicondyle
L7   Femoral epicondyle to greater trochanter
L8   Pelvic crest to acromium
L9   Greater trochanter to acromium process
L10  Acromium to ear
L11  Acromium to elbow
L12  elbow to wrist
LDG  complete landing action
ldg  landing from ground contact to CM at the bottom of the squat
LI   landing impulse
m    mass
m    metre
Ma   ankle moment
Marey Jump combined CMJ, RBJ and LDG
Mh   hip moment
Mk   knee moment
MM   net muscle moment
mr   segment mass as a ratio of whole body mass
Ms   support moment (Mk - Ms - Mh)
NDH  nominal drop height
P    visual imaging performance score
Pmm  muscle moment power
PSD  power spectral density
QSA  quasi-static analysis
RBJ  rebound jump
RMS  root mean square
RMSD root mean squared difference
RMSE root mean squared error
RNG  range
RP  visual imaging resolution performance score
rp  segment CM to proximal end as a ratio of segment length
s   displacement
scx  horizontal scale factor for film image data
scy  vertical scale factor for film image data
SD  standard deviation
SI  support impulse
SJ  squat jump
Sp  shutter pulse
T0  time at start of force capture
T1  time at takeoff for flight phase 1
T2  time at landing from flight phase 1
T3  time at takeoff for flight phase 2
T4  time at landing from flight phase 2
T5  time at end of movement sequence
t  time
TI  takeoff impulse
tof  takeoff from CM at the bottom of the squat to loss of ground contact
UA  upper arm segment
u  initial velocity
vimp  takeoff velocity calculated by integration of F2 time history
VM  video image data recorded with zoom lens matched to 16 mm image
v  final velocity
vtime  takeoff velocity calculated from flight time
VZ  video image data recorded with zoom lens
W  Winter inertia data sets
WF  Winter inertia data with Butterworth filtering
WR  Winter inertia data with no filtering
xoff  horizontal offset from centre of film image
x  medio-lateral direction
y  anterior-posterior direction (planar analysis horizontal direction)
z  vertical direction
yoff  vertical offset from centre of film image
Z  Zatsiorsky inertia data set
ZF  Zatsiorsky inertia data with Butterworth filtering
ZR  Zatsiorsky inertia data with no filtering
\phi  relative joint angle
\theta  planar orientation angle
y(a_y)  horizontal linear acceleration
z(a_z)  vertical linear acceleration
\phi(\alpha)  relative joint angular velocity
\theta(\alpha)  angular acceleration
CHAPTER 1
INTRODUCTION

Jumping and landing are the basic components of locomotion once the speed of the walking gait has been exceeded. The velocity at which this transition occurs depends upon the environment and the size of the individual. For example a short legged man will change from a walk to a run at lower velocity than a tall man. Astronauts 'walking' on the Moon displayed a distinctive hopping gait due to the low gravitational environment. Alexander (1975) showed that the velocity at which running becomes more economical than walking is determined by the square root of the product of gravitational acceleration and leg length, and hence for an adult the transition velocity is close to 3 m.s\(^{-1}\). Running is the basic mode of locomotion in sport and comprises a sequence of takeoff and landing actions interspersed with short projectile flights. Many dynamic sport activities extend this serial sequence. Hurdle clearances illustrate a motion pattern similar to running with normal strides being punctuated by slightly exaggerated takeoffs and landings. A gymnastic double somersault exemplifies the other end of the jumping and landing spectrum, with a short running sequence culminating in a single bound of extreme height.

Jumps can be categorised into single leg takeoffs to single leg landings, as in running and hurdling, single leg to double leg actions as seen in long jumping, and double to double leg contacts typical of somersaulting and vaulting. In gymnastics there are also double to single leg actions, like a 'walk-out' forward somersault, but examples of this type of jump are less common. When the human athlete is performing these dynamic actions, the same musculo-skeletal mechanisms have to cope with the high stresses and complex timing sequences of jumping and landing. In the course of this study, a variety of stylised types of jumping and landing actions have been considered. Examples have been analysed using ground reaction force data supplemented by cinefilm to examine the mechanisms and strategies employed by athletes to fulfil the different requirements of taking off from a stationary position, landing and returning to rest and combining a landing and a takeoff into a rebound jump.

This study began as an investigation into human jumping mechanics using a force plate as the primary measurement device. As time progressed more questions arose about the equipment and procedures employed to examine human jumping actions and the affects that these measurement techniques had upon the findings of this and previously published studies. As a result the overall focus of the study changed. A preliminary study (Kerwin and Challis, 1985) observed that force plate data recorded using a storage oscilloscope or transient recorder with chart recorder produced different results to those obtained when the force data were sampled via a computerised analog to digital converter. Small timing differences associated with identifying
the instances of takeoff and landing, using the two measurement systems, resulted in discrepancies in the findings. Previous studies of vertical jumping had been based on data collected using either transient recorders, oscilloscopes or galvanometers. The resulting data were presented in paper or photographic form, with force and time measurements extracted from these graphs. Small errors were inevitable with these paper based systems, and even a high quality storage oscilloscope with customised chart recorder (eg. Gould OS4100 plus Gould 60000) is limited in accuracy to between three and five percent. The effects on the flight time data alone were sufficient to show that the findings of previous researchers were questionable and that greater precision of measurement was required.

Statement of purpose

The purpose of the study was to account for the discrepancies in previous research findings concerning the benefits of muscle pre-stretching in jumping. To achieve this it was necessary to develop equipment and procedures with sufficient precision to distinguish between jumping activities with and without rebounds.

Overview

The first experimental section of this study repeated the squat, counter movement and drop jumping studies reported by Asmussen and Bonde-Peterson (1974a, b), Bosco and Komi (1978a, b) and Komi and Bosco (1978a, b). The main focus was to find out if the results obtained by these previous authors were repeatable and to discover whether improvements in the measurement procedures would influence the findings and conclusions. As a result of this study, a major investigation into the measurement equipment and procedures was undertaken. This included calibration and modal analysis of the force plate, an investigation into the frequency content of jumping and landing movements and a detailed evaluation of cinefilm and video recording equipment and processing techniques. This technical analysis formed the second part of the study and also acted as the prerequisite to the major analysis into the mechanisms of jumping and landing, which has been reported in section three. The observation made by Marey and Demeny (1885) that athletes jumped higher following a preliminary jump rather than from a standing counter movement was investigated. Cavagna, Komarek, Citterio and Margaria (1971) had started here also, but bearing in mind the limitation of the equipment used, the findings were neither conclusive nor in agreement with other studies conducted during the 1970's, (Asmussen and Bonde-Peterson, 1974a, b; Bosco and Komi, 1978a, b; Komi and Bosco, 1978a, b). This final section was a major component of the overall study. It comprised detailed studies of the integration process and its effect on the data for counter movement and rebound jumping actions. It included the determination of muscle moments about the joints of the lower limbs in takeoff and landing actions, and the calculation of muscle moment power,
angular impulse and mechanical work performed in two different takeoff and landing actions. Inverse dynamic and quasi-static techniques were examined, together with considerations of the influences of segmental inertia parameters, data smoothing and differentiation routines and the calculation procedures utilised to determine work and power in jumping and landing.

Throughout the whole of this study, equipment, data collection and data analysis procedures have been developed. In the early stages, only a force plate and storage oscilloscope were available. Computerising the data capture to enable improved accuracy of the force and time data was essential. Initially a computer (DEC PDP11/34+) and the DAOS11 language were used. A laboratory interface (CED502) was used to convert the analog output from the force plate and amplifiers (Kistler 9281B12 and Kistler 9851). The mounting of the force plate was another major consideration. The laboratory was unsuitable for a recommended sunken installation and so an alternative had to be found. A raised walkway with floor mounted frame and force plate was developed, but the natural frequency of the bolted frame was too low for dynamic rebounding activities. A new mounting frame had to be designed and built, which would have a natural frequency high enough to enable impact landings to be studied without plate resonances interfering with the force signals. Before the second study could be conducted the first computerised system became obsolete and so a completely new system was developed. A different laboratory interface (CED1401) was adopted to maintain compatibility at the binary data level, but the controlling computer and language had to be changed. A BBC Master computer with the BBC BASIC language were utilised as these were in current use in the laboratory and, when linked with the CED1401, offered high sampling rates and the required accuracy for the task. Similar developments in the visual analysis procedures had to be developed. A new cinefilm digitising system had to be created. This was based on a 16 mm cinefilm projector (NAC Motion Analyser) and high resolution digitising tablet (TDS HR48) and a microcomputer (BBC). New interfacing software had to be written, along with software to capture and store the digitised coordinates from the cinefilm records of the selected jumping actions. A detailed study of cinefilm and video equipment and analysis options had to be considered, highlighting that a high speed cinefilm camera was required. All the software for the study, with the exception of the FORTRAN implementations of three quintic spline routines had to be written. Although initially written on a BBC Master computer, all the analysis programs have subsequently been modified to run under RiscOS 2.0 on an Archimedes 400 series computer and more recently to RiscOS 3.1 and RiscOS 3.5 on a RiscPC computer with an ARM 710 processor. The programs comprised:

- synchronisation and data capture and analysis for cinefilm and force plate
digitisation, scaling and rotation of raw digitised data
padding, filtering and interpolation of film data
determination of additional body segment inertia parameters
determination of whole body mass centre locations, velocities and accelerations
determination of knee joint centre locations, trunk and neck angles
integration of force data without and with correction
inverse dynamic analysis of jumping and landing
quasi-static analysis of jumping and landing
muscle moment power, energy and angular impulse determination
point mass energy analysis
all the graphical presentations with the exception of the regression analyses
file conversion routines to enable data from different sources to be combined

There were too many programs in total to include in the thesis, and so the main programs only have been included in a separate appendix (B).

The study has therefore comprised two parallel tasks - developing the laboratory, equipment and software to enable a biomechanics research study of jumping to be undertaken and carrying out the research study. As technology has advanced during the time that the study has been ongoing, many of these tasks have had to be completed more than once. If the same study was to be undertaken today with the use of an automatic motion analysis system with simultaneous force plate data capture like CODA mpx30, Vicon 370 or MacReflex, the same data collection and reduction could be achieved in a very small fraction of the time. Similarly, many of the data processing routines, which had to be written are currently available within commercially available systems. It is hoped, therefore that not only insights gained within this study can be utilised in the future, but also that larger numbers of activities within larger subject pools and with many more trials can be investigated. The aim is to increase understanding of the fundamental human skills of jumping and landing. Even with sophisticated muscle and whole body forward dynamic modelling approaches developed and utilised by Soest, Schwab, Bobbert and Ingen Schenau, (1993), and Pandy and Zajac, (1991), the skill of vertical jumping is still not well understood. Hay (1973) commented that the vertical jump is by no means a simple skill and emphasised the need to understand two segment motions fully, before trying to analyse multi-articular systems. The role of bi-articular muscles, for instance, is still not well understood. Ingen Schenau, Bobbert and Rozendal (1987) argue in favour of proximo-distal power transfer while Pandy and Zajac (1991) favour enhanced coordination as the primary function. These differences serve to highlight that the two distinct groups, although using similar models, agree more closely each year on the contributions of different muscle groups to jumping performances, but they are still not able to agree about the role of the bi-articular muscles in vertical jumping.

Chapter Organisation

Following this introduction, Chapter 2 contains a review of literature, beginning with an overview of the development and use of the force plate in biomechanics research. This has been
followed with an evaluation of a series of studies of squat, counter movement and drop jumping mainly based on force plate studies conducted in laboratories. Elastic energy and its role in jumping has been evaluated, and the methods and observations of a number of researchers (Asmussen and Bonde-Peterson 1974a, b; Bosco and Komi, 1978a, b; Komi and Bosco 1978a, b) have been questioned. The next section of the review has concentrated upon technical aspects of the equipment and protocols used in previous and current studies. The topics, included in this section, comprise force plates and mountings, frequency analysis of equipment and human movements, signal processing including data synchronisation, filtering, integration and differentiation. In addition, film image digitisation and coordinate transformations, joint centre determinations and human body segmental inertia parameters have been examined. In section four of the review, attention has been focussed on inverse dynamic analyses of jumping activities. Single and double leg takeoffs, rebound jumps and drop landings have been included. Muscle moments about the joints of the lower limbs, segmental energy and power transfers between segments were considered along with measures of angular impulse. Finally forward dynamic modelling of human jumping has been reviewed. The development of modelling in general and in relation to studies of human jumping in particular have been included. Alexander's (1990) single muscle model of high and long jumping takeoffs, together with his two joint throwing models (1991), were highlighted as powerful examples of the ways in which simple models can contribute in understanding the fundamentals of human motion. The work of Ingen Schenau's Amsterdam research group has been compared with that of the Stanford based group working with Zajac. In addition some aspects of wobbling mass modelling of impacts, related to drop landings, have been considered. In each section of the review, emphasis has been placed on those aspects of previous research which were of major relevance to the methods and problems within the current study and which raised questions to be addressed within the course of the ensuing investigations.

Chapter 3 is the first of three experimental chapters. It has reported an experimental examination of the methods and findings of previously reported studies of vertical jumping. Initially, the procedures described by Cavagna (1970), Asmussen and Bonde-Peterson (1974a, b), Bosco and Komi (1978a, b) and Komi and Bosco (1978a, b) were investigated. Three styles of jumping were considered; squat jumping (SJ), counter movement jumping (CMJ) and drop jumping (DJ). All three jumps were performed on a force plate so that the ground reaction forces could be measured. The squat jump was performed from a stationary squatting position on the force plate, and then the legs were extended without any preliminary downward or bouncing motions. The counter movement jump began with the subject in a stationary standing position on the force plate, and was followed by a downward drop into a squat position and immediate extension into the jump takeoff. The drop jump began with the subject in a stationary standing position on a raised platform close to the force plate. They then stepped off the platform, and dropped and rebounded from the force plate. The heights from
which the drop jumps were performed ranged from 0.15 m to 0.90 m, and the tasks were performed by male and female subjects.

Chapter 4 has detailed the equipment, procedures and analysis methods, which were evaluated and developed, or modified to enable some of the unanswered questions from Chapter 3 to be addressed. Throughout the study, the use of the force plate for analysing a variety of human jumping actions remained the major theme, but interwoven within this investigation were other challenging technological investigations, concerned with mounting of the force plate, recording and digitising of cinefilm and processing of the resulting force and image data. The effects of numerical differentiation have been widely examined in the research literature as highlighted in Chapter 2, but far less attention has been devoted to the process of numerical integration. The effects of sampling rates and integration protocols on the resulting data, and hence the findings of studies based totally on force plate data, have been considered.

Chapter 5 contains the major part of the thesis. Many of the findings reported by other researchers (Asmussen and Bonde-Peterson, 1974a, b; Bosco and Komi, 1978a, b; Komi and Bosco, 1978a, b) and repeated in Chapter 3 could not substantiated. The 'simple' measures of elastic energy and its contribution to enhancing performance were not observed. The concept of an 'optimum drop height' for use in rebound jumping activities could not be found. A more detailed study of the actions of taking off and landing was therefore undertaken. Inverse dynamic analyses of two takeoff and two landing actions were completed. All the techniques established in Chapter 4 were utilised and consideration of inverse dynamic and quasi-static methods for estimating muscle moments were considered. The influence of using different body segment inertia parameters, data filtering and differentiation procedures with the inverse dynamic analyses were evaluated. The calculation of segmental energy and muscle moment power contributions were established, and joint angular impulses were used to study the similarities and differences between takeoffs, following a counter movement and a rebound landing, and landings preceding a rebound and prior to coming to rest.

Chapter 6 contains a summary of all the observations and findings within the thesis and looks towards the future with a consideration of human body modelling software and the role of computer simulation in enhancing understanding of human movement. The rate at which computing equipment and software has advanced during the past ten years has already changed many of the regularly accepted practices in sports biomechanics and opened up new opportunities for the development of rapid and convenient procedures for experimental and modelling studies of human motion.
CHAPTER 2

REVIEW OF LITERATURE

2:1 INTRODUCTION

The literature review focuses primarily on studies of jumping. Other topics have been included only when a relevant feature has been highlighted particularly well by an example from another aspect of human movement analysis. The review chapter is divided into three main sections; force plates, kinematics and modelling.

The first section of the review contains a brief overview of the historical development of the force plate as a measuring instrument. This is followed by a consideration of the use of force plates in the biomechanical study of human movement in general. This section is concluded with an examination of those studies in which force plates have been employed in the study of human vertical jumping and landing which have highlighted many of the discrepancies found in previously published research.

Section two of the review concentrates on the underlying technical aspects of the measuring systems, and data collection and analysis protocols associated with the studies of jumping and landing. These include a consideration of force plate calibration, natural frequency, and data collection and analysis methods. Video and cinefilm recording media, kinematic data management techniques required for noise reduction and differentiation purposes and a consideration of anthropometry and segmental inertia parameters have also been covered.

The final section focuses on modelling, and ranges from inverse dynamics, to energetics and forward dynamics. The ideas associated with modelling of the human body have been considered. Resultant joint forces, muscle moments and joint power have been examined in relation to jumping. Quasi-static, in addition to inverse dynamic techniques, have been featured. Energetic analyses have proven challenging and largely unrewarding, but some of the ideas associated with treating the body as a point mass or a segmental linked system have been explored. Finally, forward dynamics models, which combine models of skeletal muscle with dynamic system representations of the human body have been reviewed. These range from two segment, single muscle models designed to provide insight into jumping strategies to multi-segment, multi-muscle models designed to explain coordination and power production in human jumping.
Introduction

The force plate is a piece of equipment which has been used in jumping studies either on its own or in combination with other recording equipment. However, despite its popularity as a piece of data acquisition equipment, the force plate has received far less reported attention in terms of calibration than, for example cinefilm. This part of the review looks at all of the key issues relating to the force plate as well as reviewing those jumping studies which have used a force plate.

Historical perspective

The measurement of ground reaction forces has been a valuable source of information in the study of human motion. Nigg (1994) reported on the early developments of pioneers (Carlet, 1872; Marey, 1873) who produced pneumatic sensors capable of measuring forces between the foot and the ground. Marey's version was portable and so founded a line of research into foot pressure distribution which has been developed more recently using strain gauged sensors (eg. Soames, Blake, Stott, Goodbody and Brewerton, 1982; Gerber, 1982) and resulting in the development of capacitor based instrumented insoles which have been produced commercially for example by the Emed and Kraemer Companies. The idea of using a fixed plate for force measurement was extended to the point where Elftman (1939) described a new instrument, which he had referred to in a paper published in the previous year. He wrote -

"a new apparatus has been devised which gives not only the point of force application of this force, but also the magnitude of the force components".

The Swiss Company Kistler produced the first commercial piezo electric force plate in 1969 for the Zurich laboratory run by J. Wartenweiller, one of the founder members of the International Society of Biomechanics. The American Company AMTI constructed the first commercial strain gauged force plate in 1969 for use in a Boston Children's hospital. In the last ten years another company (Bertec) has introduced a range of strain gauged plates with integral amplifiers, and honeycombed top plates providing great rigidity with low mass. A rigid top plate and high natural frequency are essential characteristics for the measurement of human motion involving impacts, and are characteristics that a number of the earlier, individually designed, force plates could not claim. Payne, Slater and Telford (1968) reported force data for a variety of athletic activities which clearly showed residual resonances in the force trace after the athlete have left the force plate surface in a jump. The majority of current research uses one of the three commercially available units.
Interest in the force plate as a measuring instrument has been wide ranging from studies in gait, sport, human power output, neural control and the maintenance of balance. Force plates have been used so extensively in the study of human vertical jumping that this has been treated as a separate section within the review chapter. Gait studies have been of interest since the innovative photographic studies produced towards the end of the last century by Marey and Muybridge. However, the milestone biomechanical gait study was produced by Elftman (1939). He cited the previous attempts to quantify locomotion including the work of Webers, Marey, Otto Fischer, Bernstein (1927, 1935) and Fenn (1929, 1930). Elftman's study was a truly monumental effort in which he combined the "new apparatus" (force plate) with cinematography to produce an inverse dynamics analysis of human locomotion. Forces, moments and segmental energy changes were quantified without the aid of the computing and digitising systems that are taken for granted today. It laid the foundations for studies of human and animal locomotion and has been referenced frequently by those adopting the inverse dynamic approach. Elftman pointed out that the advent of the force plate enabled analyses of just the lower limb to be undertaken without the necessity to analyse the motion of the whole body. Elftman (1940) followed his walking study with one on running. This was unusual since ground reaction force data were not available (the film was provided by another researcher) and so Elftman calculated the ground reaction forces from the whole body mass centre motion. Even with modern computing methods, this still proves a challenge in modern biomechanics and therefore it is unlikely that the forces calculated by Elftman, particularly at impact, closely match the transients that have been reported more recently (eg. Cavanagh and Lafortune, 1980).

The "Californian Contribution", reported by Paul in Cappozzo, Marchetti and Tosi, (1992), continued this line of enquiry. The work was undertaken between 1945 and 1947 and concentrated on design specifications for artificial limbs. The research group developed two force plates to overcome some of the problems associated with obtaining force data during the double support phase of walking. They also used three orthogonally located 35 mm cinefilm cameras and cortical pins to monitor bone movements (also used by Lafortune in 1987 for studying tibial acceleration when landing from a jump). Because the images were used independently rather than in a 3-D reconstruction, there were errors in the pin orientation angles of between 2° and 10°. The Californian research was very extensive with additional studies being conducted using EMG, glass walkways, force measurements from limb pylons and interrupted light photography. The volume of data from this innovative and wide ranging research programme was so extensive that much of it was never analysed. Bresler and Frankel (1950) developed this line of enquiry with studies of forces and moments in level walking. Four subjects were analysed and moment of inertia data measured using a 'quick release' method were reported. When the very limited data reduction and calculating technology available at that time are taken into consideration, this study, along with those of Elftman some ten years earlier, are quite remarkable.
Paul (1964, 1966, 1971) used three-dimensional inverse dynamic analysis to examine the loads at the human hip. The approach taken was to reduce the number of unknown forces at the hip to the number of equations describing the resultant moments and forces at the hip, thus making the system determinant. The reduction was achieved by functionally grouping muscles together, and using EMG to identify when certain muscles (groups) were inactive and so could be ignored for given phases of the movement. A similar approach was taken for the human knee by Morrison (1968), and ankle joint complex by Proctor and Paul (1982). Smith (1972, 1975b) used dry bone modelling techniques, normally associated with medical research applications, to investigate bone and tendon forces in an athletic drop landing task. He showed that the internal forces were very much larger than those previously recorded in walking, stair climbing and other daily routine activities. Winter (1979) reported two-dimensional inverse dynamic studies of walking using video based kinematic data combined with AMTI force plate data. Winter's approach has been used extensively in two dimensional gait studies and in sports analyses.

Gait studies using force plate data form a major part of current research in biomechanics. These have ranged from studies in which force data have been used to evaluate algorithms to predict heel strike transients, (Bodland and Thornton-Trump, 1987), through methods to quantify force traces in gait using Fourier transformations, (Alexander and Jayes, 1983; Antonsson and Mann, 1985). Zarrugh (1981) studied intersegmental loads in gait and also considered power transformations at the joints in walking. Chao, Laughman, Schneider, and Stauffer (1983) reported normative force time histories of gait patterns. Force plates are accurate and reliable and therefore are often used to evaluate models of human locomotion and jumping (Bobbert, Huijing and Ingen Schenau, 1986; Blickhan, 1989; Pandy, Zajac, Sim and Levine, 1990).

Force plates have been used extensively in the study of body sway (Deborah and Hayes, 1985; Goldie, Bach and Evans, 1989; Hufschmidt, Dichgans, Mauritz and Hufschmidt, 1980). Ground reaction forces and centre of pressure pathways have been recorded during single (Tropp, Ekstrand and Gillquist, 1984) and double leg standing (Murray, Seireg and Sepic, 1975) and for the study of neural damage (Thyssen, Brynskov, Jansen and Münster-Swendsen, 1982; Jansen, Larsen and Olesen, 1982; Hasan, Lichtenstein, Shiavi, 1990). Sway amplitudes and sway frequencies have also been used to compare human stability in erect standing and inverted (handbalancing) postures (Slobounov and Newell, 1996). These studies appear on the border between biomechanics and the motor control aspects of psychology.

Force plates have also been used by physiologists and biomechanists to examine human power output. Sargent (1921) described a physical test of man, which was a test of 'power'. An early study in which vertical jump was used to consider power output was conducted by Davies (1971). He referred to a previously published abstract (Davies and Rennie, 1968) to describe the methods used to calculate power. The force-time trace was integrated and then the product
of the resulting velocity and corresponding force data were used to determine instantaneous power values. Davies (1971) presented data on 47 males and eight females aged between 20 and 50 years and compared power output values from vertical jumping and stair climbing. The values he found were amongst the highest ever recorded (5.22 horsepower, 3.89 kW, for the males and 31.5 hp, 2.35 kW, for the females) and were described by Davies as being close to the theoretical maximum that a human is capable of producing. In trying to account for the very large values obtained he suggested that some energy from the initial part of the jump may have been stored and used in the push off phase. In this sense he was preempting the studies of Asmussen and Bonde-Peterson (1974a, b) and Komi et al. (1978a, b) in considering a role for elastic energy in counter movement vertical jumping. Luhtanen and Komi (1979, 1980) used force plate data in the study of power output in long jumping, walking, running and other forms of jumping. Winter (1983) reported moments and power values in jogging and with various colleagues (Quanbury, Winter and Reimer, 1975; Robertson and Winter, 1980) looked at segmental power and energy flows in walking. The whole area of human power output has received considerable attention and as it is central to the analysis of the rebound jumping covered in Chapter 5, will be examined in more detail later in this review.

**Impact Landings**

Human impact landings introduce particular problems in biomechanics. Modern force plates and recording systems have the required frequency response to be able to faithfully record the transients at the moment of impact and have been used in the study of the dynamics of these rapidly varying events. Hospach (1992) introduced the idea of a wobbling mass model when comparing landing forces produced by a human and a crash dummy. She showed that the introduction of wobbling masses into models of the human body produced superior agreement between measured and predicted ground reaction forces during landings and also showed that the constraint forces at the knee were only 25% of the magnitude and in the opposite direction to those calculated using a rigid model. These observations have implications for inverse dynamic analyses and clearly provides an area of future research which will need extensive investigation. Denoth, Gruber, Keppler and Ruder (1984) calculated the forces and torques during sports activities with high accelerations and highlighted the particular problems associated with the initial impact phase. They showed that a "wobbling mass" model was necessary to determine high impact landing forces. They were specifically referring to the peak at impact over the first 20-30 milliseconds and showed that, even with the use of very high speed cinefilm, the linear accelerations, experienced by the bony structures of the body were close to 600 m.s\(^{-2}\), and could not effectively be recorded. They therefore used a modelling approach and were able to show that the muscles played a very minor role in the early phases of impacts and it was not until after the muscle forces built up that they contributed to the deceleration of the body. More recently Dufek and Bates (1992) developed lower extremity performance models for landing whilst
Stacoff, Kaelin and Stuessi (1988) examined impact landings following a volleyball block. Volleyball has been a focus of a number of studies, although the majority have concentrated on the takeoff rather than the landing phase (Wieki and Dangre, 1985; Coutts, 1982). The fact that volleyball players are skilled jumpers makes them a subject of interest for two reasons. Firstly they provide good examples of strategies for jumping high. This is of interest to those researchers studying coordination and power production in jumping, (Bobbert, Huijing and Ingen Schenau, 1987a, b; Bobbert and Ingen Schenau, 1988; Hay, Dapena, Wilson, Andrews and Woodworth, 1978) and also to those developing models of human jumping, (Alexander, 1992; Soest et al. 1993; Fujii and Moriwaki, 1992; Bobbert et al. 1986; Pandy et al. 1990; Pandy, 1993; Pandy and Zajac, 1991; Anderson and Pandy, 1993). Secondly volleyball players jump and land regularly and so are of interest when studying the aetiology and mechanics of injury. Stacoff et al. (1988) showed that although the impact forces were as high as 6000 N, it was the use of knee flexion which was the major factor in reducing the likelihood of pain and injury. Similarly gymnastics is another sport in which skilled jumping and landing actions are well represented. Panzer (1988), Sanders and Wilson (1992), Sanders and Allen (1993) and McNitt-Gray (1993), McNitt-Gray, Yokoi and Millward, (1993) are examples of force plate studies in which landing forces have been studied in attempts to gain more insight into the causes of injury. A more conventional force plate study in gymnastics has been reported by Miller and Nissinen (1987). They examined the ground reaction forces in running forward somersaults, to gain insight into the effects that these forces had on the resulting performance. They showed that in the horizontal direction braking dominated and that the peak vertical forces were in excess of 13 bodyweights. They also showed eccentric ankle and knee extensor activity beyond the time when the lowest mass centre displacement occurred.

**Applications in Sport**

Steele and Milburn (1988) examined the effects of different synthetic sports surfaces on ground reaction forces when landing in netball, but the most extensive study of the influence of surface materials on impact forces have been undertaken by researchers interested in the design of running shoes, (eg. Clarke, Frederick and Cooper, 1983; Frederick, Clarke and Hamill 1984). A similar investigation by Luethi and Nigg (1985) concentrated upon the influence of different tennis shoe constructions on discomfort and pain. This was a comprehensive study with force plate data on over 200 subjects being recorded.

The classic and often quoted study of ground reaction forces in distance running by Cavanagh and Lafortune (1980) identified rearfoot and forefoot strikers through the transposition of centre of pressure data from the force plate surface to the soles of each runner's shoes. Andriacchi, Goldflies, Galante and Stern (1981), and Simpson and Bates (1990) examined moments exerted in the lower extremities and the effects of running speed on lower extremity joint moments.
respectively. Although the three components of ground reaction force and the point of force application or centre of pressure are regularly recorded, the free moment about the centre of pressure appears to be conspicuous by its absence. Holden and Cavanagh (1991), however, did make use of this variable in studying pronation changes with differing shoe inserts.

Biomechanical studies of long jump takeoffs have made use of force plate data. This is not surprising since it is the ideal jumping event in which the small size of the force plate as a target is not a limitation, but rather a prerequisite for the event. The topics of study have varied from those by Ramey (1970, 1973a) in which quantifying the forces in the long jump takeoff was the goal to the those aimed at determining angular momentum in takeoff using a force plate (Ramey 1973b; Bedi and Cooper, 1977). Both of these combined cinefilm, and data from a strain gauged force plate, to study the takeoff actions. By combining the ground reaction force vector with the time synchronised position of the mass centre of the athlete, the turning moment could be determined and the integral of this moment time curve used to quantify changes in angular momentum throughout the takeoff action. Bedi et al. (1977), in analysing eight collegiate long jumpers, highlighted differences of 33% in angular momentum compared with values determined from film alone and attributed these variations to the high sensitivity of synchronisation between body position and force vector data. This matched the criticism of the Ramey (1973) method for determining angular momentum by Hay, Wilson and Dapena (1977). Using film based analyses, Hay et al. (1977) highlighted the extreme sensitivity of the horizontal displacement of the mass centre with respect to the ground reaction force vector and advised against the use of this technique.

There have been a number of studies of high jumping (Dapena, 1987; Dapena and Chung, 1988) but the use of force plates in high jump studies is quite rare. Deporte and Van Gheluwe (1989) used two 0.9 m x 0.6 m force plates to record ground reaction forces for two male high jumpers. Both were elite athletes having achieved clearances at 2.32 m and 2.42 m. The purpose of the research was to obtain data which hopefully might lead to a better understanding of the causes of pain and injury in jumping. One interesting finding was that the impact force for both jumpers and for all heights jumped were similar but that the active or push off forces were greater for the lower of the two jumpers. Dessurealt and Lafortune (1981) showed that the impact and active forces for flop style jumpers were lower than for straddle jumpers and suggested that this may have been one of the key reasons for the popularity of the flop technique. Kilani and Adrian (1985) reported a multi-instrument analysis of high jumping which included instrumented insoles and force plates but the paper was almost totally methodological.

Investigations in gymnastics included an early force plate study comparing the take-off forces in flic-flacs and back somersaults by Payne and Barker (1976). Brüggemann (1983) combined
cinefilm and force data in an analysis of backward somersault take-offs from the floor, and Watkins and Nicol (1986) used the techniques proposed by Alexander and Vernon (1975) in an analysis of the leg action in a round off flic-flac takeoff. This was unusual in that quasi-static rather than inverse dynamic techniques were used. Another unusual study used the force plate alone to determine angular momentum in the takeoff for a flic-flac, Kerwin (1992).

In all the above studies, force plates have been located in the floor of a laboratory, gymnasium or running track. Force plates have been used located in less obvious locations for the study of sporting activities, including a suspended target used to measure lunge forces in fencing (Kerwin 1985). Four unusual studies have used force plates in the competition venues. Doris Miller studied takeoffs from the surface of a 10 m diving platform in the 1990 World Diving Championships in Milan, and in the 1996 Olympic Games in Atlanta. Komi used a specialised force plate in the takeoff ramp for the ski jumping competition at the 1988 Winter Olympics. Baumann and colleagues collected data from force plates at the 1985 World Weightlifting Championships (Baumann, Gross, Quade, Galbierz and Schwirtz, 1988). These studies are of note since they obtained data during major world competitions. The data obtained are therefore of special interest. For example the study by Baumann et al. (1988) on the snatch technique of world class weightlifters reported the use of two Kistler force plates which had been located in the competition platform and used as the standing surface for the lifters. The data obtained were combined with three-dimensional video data enabling an inverse dynamic analysis of the lifting actions to be quantified. Despite these examples there are still very few studies in which force plates are used during competition and probably this will remain the case whilst rigid top plates remain the contact surface between the athlete and the measuring transducers.

**Vertical Jumping Studies**

Variations on human vertical jumping have been investigated with force plates since the first pneumatic devices were invented. A Sargent jump test (Sargent, 1921) requires an athlete to perform a counter movement followed by a coordinated arm swing and leg extension with the aim of attaining maximum reach height. Because skilled timing of the reaching action is required this is not the best test of leg function in jumping and so most force plate studies have used modifications of the Sargent jump test in which the height attained by the subject's mass centre (Offenbacher, 1970) has been used as the measure of performance. These variations on jumping style have required subjects to keep the hands on the hips in an attempt to focus all the activity in lower limbs. This approach has been particularly popular in those studies which have sought to quantify elastic energy.

Marey and Demeny (1885) instigated an on-going area of research into the apparent utilisation of elastic energy in jumping with their observations that heights attained during a jump preceded
with a preliminary jump were greater than those without an initial jump. These comments were
based on direct observations of people jumping either from a standing position or when
preceded by a preliminary jump. The elastic properties of muscle have long been studied,
although Levin and Wyman’s (1927) ideas on contraction force being turned into strain energy
for subsequent release were shown to be inappropriate by Fenn and Marsh (1935). Isolated
muscle experiments (Cavagna, Dusman and Margaria, 1968) demonstrated that an in vitro
muscle was able to produce greater contractile force if preceded immediately by an eccentric
contraction. The same group also showed that this muscle stretch shortening cycle appeared to
have beneficial effects on work output using ergometry:

*The positive work performed by a muscle during a given shortening at a given speed
on a Levin and Wyman ergometer may be appreciably greater when the shortening is
preceded by stretching the contracted muscle.*

*Cavagna et al. (1968)*

Cavagna, Komarek, Citterio and Margaria (1971) investigated this effect with a jumping study
onto a force plate. They used three types of jumps. The first from a squat position, the second
from a standing position in which the subject performed a counter-movement downwards
immediately prior to the upward jump, and the final was a repetition of the successive jumps of
Marey and Demeny (1885), cited by Asmussen and Bonde-Peterson (1974a). The first two of
these were described as static (or squat) and counter movement jumps (Asmussen and Bonde-
Peterson 1974a). Cavagna et al. (1971) concluded that there was no significant difference
between the counter movement and successive jump performances and that performances under
the static and counter movements were also similar. Their sample was small with only five men
and two women. Also the body mass ranges were 56.1 kg to 80 kg. They did report peak power
values of the same order as those reported by Davies and Rennie (1968). Interestingly
Asmussen and Bonde-Peterson (1974a), re-examined the data from the Cavagna et al. (1971)
study and showed using a Student’s ‘t’ test that

... a counter-movement de facto results in a significant increase in the velocity of
take-off of 6.4% (p<0.01), corresponding to an increase in height ... of 11.3%, ie.
twice the average increase in our data.

*Asmussen and Bonde-Peterson (1974a), p392.*

Thus although Cavagna et al. (1971) had demonstrated differences in performance in terms of
peak power they commented on the observations of Marey and Demeny (1885), that the second
jump was higher than the first because of the elastic energy stored at the end of the first jump,
were not supported.

*This (the second jump being higher than the first) is not substantially confirmed by
the present experiments, which indicate that the previous stretching does not
appreciably increase the amount of positive work done. Cavagna et al. (1971).*
Asmussen and Bonde-Peterson (1974a) studied 19 subjects, including 5 females who performed static and counter movement jumps, together with a series of depth jumps from platforms at heights of 0.233 m, 0.404 m and 0.690 m. They reported significantly improved jump height performances in comparison with the jump heights attained from a static position. These improvements were 11.5 per cent when dropping from the 0.404 m platform and 5.5 per cent for the counter-movement. They also attributed the reduced performance from the 0.690 m platform to "conscious inhibition". The papers reported by Asmussen and Bonde-Peterson (1974a, b) described the force plate they used as being slightly "under damped" and with a natural frequency of around 50 Hz. The data are therefore less reliable than would be obtained from a modern commercial force plate and should be treated with caution. In 1978 Komi, in association with Bosco, commenced a series of studies utilising the procedures outlined by Asmussen and Bonde-Peterson (1974a). Komi and Bosco (1978a), conducted a study into the utilization of stored elastic energy in leg extensor muscle by men and women. Three groups were included, 25 female physical education students, and two groups of 16 males, one comprising physical education students and the other volleyball players. They each performed a series of static, counter movement and rebound jumps from varying drop heights ranging from 0.20 m to 1.00 m. In all cases the static jump technique resulted in the poorest jump height. They claimed a remarkable difference in the capacity to utilize elastic energy stored during the counter movement between the females and the males, with approximately 90 percent recovery for the women compared to about 50 percent for the men. Interestingly, using their calculation procedures, the percentage return decreased dramatically as the height of drop increased. For the females the value decreased to below 25 percent and values for the males to less than six percent. They concluded that the males performed best from a drop height of between 0.63 m and 0.66 m whilst the females best performance was achieved from a drop height of 0.475 m. These were mean values for the groups and do not correspond to the actual heights dropped. Unfortunately this experiment had many weaknesses. The testing conditions for the females were different to those for the males. The women dropped from seven heights increasing in 0.10 m steps from 0.20 m, whilst the males only performed drop jumps from heights of 0.26, 0.45, 0.62 and 0.83 m. No specific statistical analyses were described, although it was stated that

*In all groups, the static jump condition was significantly (p<0.01) the least efficient condition as compared to the performance in counter-movement and drop jumps. These two latter conditions showed no significant differences in performance in any of the groups studied. Komi et al. (1978a), p. 263.*

The repeated use of paired 't' tests by Asmussen and Bonde-Peterson (1974), was criticised by Bedi, Cresswell, Engel and Nicol (1987). In particular they pointed out that Asmussen and Bonde-Peterson's (1974a) statistical data analyses were inappropriate on the basis that
The inclusion of the female subjects and the use of a multiple paired 't' test may confound the results and invalidate the conclusions. Bedi et al. (1987), p11.

They also criticised the studies of Bosco and Komi (1978a, b, and 1980b), on the basis that no statistical tests on heights of jump attained were reported. Also in a later study, Hakkinen and Komi (1983) did perform statistical comparisons on 'before' and 'after' training effects but did not report any differences across dropping heights. As a consequence, they conducted a new experiment in order to assess if a relationship existed between maximal jumping performance and the effect of stretch loading the extensor muscles, by dropping from increasing heights prior to rebound vertical jumping. Two distinct groups of male subjects, all between the ages of 19 and 26 years, were formed from 12 volleyball specialists and 20 physical education students, none of whom were specialised jumpers. All subjects performed five jumps from each of eight heights in random order with five minute rest periods between each set. The heights were 0, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75 and 0.85 m. The zero dropping height was a counter movement jump. These methods corresponded closely to those advocated by Asmussen and Bonde-Peterson (1974b) and Bosco and Komi (1978a, b), with the exception that the above set of heights consistently represented smaller increments over the range than were employed by either of the other two groups of investigators. At the analysis stage the study was distinctly different. Bedi et al. (1987) employed an Analysis of Variance design with one grouping factor and repeated measures across the depth jump heights. Following a main effects test, Tukey tests of ordered means were performed as required. An alpha level was chosen at 0.05. They reported a highly significant grouping effect, \( p<0.001 \), with the volleyball players jumping higher than the physical education students under all conditions. They also noted that the counter-movement jumps were better than any of the drop jump performances for both groups \( (F[7, 210] = 8.25, p<0.001) \), and that there were no significant differences between the performances of vertical jumps after a prior drop from any height. These findings applied for both the average and the best performances. Finally Bedi et al. (1987) made the concluding remark that

The data from other published reports on this topic appear consistent with the concept that there is no difference between the performance when dropping from different heights. Bedi et al. (1987), p11.

These experiments showed weaknesses in the methods employed by the other researchers, to whom they had made reference. These included Asmussen and Bonde-Peterson (1974a, b), and the work of Bosco and Komi (1978a, b, 1979a, b) and Komi in association with Hakkinen (1983), all of whom claimed to have demonstrated an optimum dropping height for maximal performance. In the light of the Bedi et al. (1987) study, the validity of the previous work is thrown into doubt, and the subsequent use of drop jumping as a means of testing performance improvements as a result of plyometric training must also call into question the appropriateness of any associated 'research evidence'. Interestingly Bedi et al. (1987) did not comment on the
methodology of the force and time data collection and analyses. They employed a force
electrical frequency of 200 Hz and assumed that the practice sessions provided for their 32
subjects prevented them from, deliberately or inadvertently, influencing their dropping heights.
Kerwin and Challis (1985) identified a tendency in all subjects to alter their dropping strategy as
the height of the platform increased. In particular a discrepancy between the nominal height and
the actual height dropped was identified. Numerical integration techniques were used to
determine the vertical ground reaction force impulses. It was found that when the platform was
raised above 0.45 m, the subjects reduced the height from which they dropped. This is in
agreement with Asmussen and Bonde-Peterson's (1974) suggestion that "conscious inhibition"
was present at their highest drop height (0.690 m). Kerwin and Challis (1985) also identified
the fact that in the studies of Asmussen and Bonde-Peterson (1974a) and Bosco and Komi
(1978a), flight times were identified from transient recorder hardcopy traces. In the study by
Kerwin and Challis (1985) the reliability of this form of time data acquisition was seriously
questioned since only 50 per cent of the variability in jump height could be accounted for on the
basis of time of flight. Using a finer time resolution based upon computerised ADC readings,
the correlation coefficient was 0.955 with a standard error of +/- 0.0004m, (n=52). It was thus
recommended that flight time data should only be used to predict jump height if a suitably small
time resolution was employed, and that time data determined from chart recordings, irrespective
of the use of transient recorders, should not be used for this purpose. The resulting errors
accrued from this form of time determination degrade the quality of the flight data, and when
this is linked to the error associated with using the nominal rather than actual drop height, the
information derived from their analyses should be regarded with extreme caution.

Aura and Viitasalo (1989) reported on a series of seven jumping exercises including single and
double leg landing drop jumps, and long and high jump takeoffs by four athletes to determine
what they referred to as 'selected biomechanical characteristics of jumping'. It was clear from
the fact that this descriptive paper was published, that although jumping has always been a focus
of biomechanical study, relatively little is still known about the forces, timing and segmental
actions associated with dynamic jumping skills by athletes. This is in contrast to the relatively
large amount of attention devoted to squat jumping, counter movement jumping and drop
jumping which have been the centre of attention since the 1960's and has provided an invaluable
series of protocols over the past thirty years, (eg. Cavagna et al. 1971; Asmussen and Bonde-
Peterson, 1974a; Bosco and Komi, 1978a; Soest et al. 1985; Bobbert et al. 1987a; Pandy and
Zajac, 1991). Bobbert and Ingen Schenau, (1987) compared studying jumping style in good and
poor jumpers by analysing the jumping performances of ten volleyball and ten handball players
executing vertical jump takeoffs. They hoped to determine factors which distinguished good
jumping technique from poorer technique. They found that that volleyball players jumped on
average 11 cm higher after takeoff than the handball players and attributed this largely to a
smaller hip angle at the start of the push off phase and hence a greater time and distance over
which to apply force. They were unable to determine whether the greater performance was due to differences in power output capacity or improved coordination.

The studies in which the force plate data alone has been used have provided a series of conflicting findings. Those papers supporting stretching the leg extensor muscles prior to jumping as a way of enhancing jumping performance include Asmussen and Bonde-Peterson, (1974a); Bosco and Komi, (1978a, b); and Komi and Bosco, (1978a, b). Papers finding no differences in jump height attained when using squat and counter movement jumping techniques include Cavagna et al. (1971) and Bedi et al. (1987). Bober et al. (1987), when studying kicking rather than jumping leg extension with and without eccentric contraction, found increases in final leg extension velocity, following eccentric action, only when the joint range of motion was small. Asmussen and Bonde-Peterson, (1974a), Bosco and Komi (1978a, b) and Komi and Bosco (1978a, b) found that dropping prior to performing a counter movement facilitated improved jumping performance. In contrast Bedi et al. (1987) showed that the counter movement produced better jump heights than any of the drop jump performances and that there were no significant differences between the jump heights attained from the range of drop heights used (0.02 m - 0.85 m). The protocols adopted for performing the jumps were basically the same in each study, but the means of quantifying the performances and the use of statistical tests when evaluating the data varied.

It therefore became clear that there was a need to conduct a new series of jumping trials with improved standardisation of recording and analysis procedures. Static (or squat) jumping in comparison with counter movement and drop jumping were recorded in an attempt to resolve the apparent disagreements between the findings of previous studies and have been reported in Chapter 3.

2:3 ANALYSIS SYSTEMS

Introduction

The discrepancies related to analysis methods, which were highlighted by the force plate studies of jumping, also raised a number of more general questions about the force plate and other technologies which have been used widely in the study of human jumping. This section of the review has therefore included a detailed analysis of the force plate as a measuring instrument. Included within this section are reviews of the influence of the mounting systems used for force plates, calibration of force plates, frequency analysis of human movement and of force plates.
Early studies of jumping used force plates either as sophisticated timing mats, or to record vertical force time data for integration (eg. Cavagna, 1970; Bosco and Komi, 1978a, b). More recent studies of jumping have progressed to those employing inverse dynamics analyses (eg. Ingen Schenau, Bobbert, Huijing and Woittiez, 1985; Bobbert et al. 1986) and forward dynamics modelling (Pandy et al. 1990; Soest et al. 1993). It was therefore necessary to examine the additional related topics of visual recording and digitising systems, synchronisation of kinematic and force plate data, data management protocols including filtering, differentiation, skin marker movement, joint centre location and the selection and influence of body segment inertia parameters in experimental and modelling studies.

**Force Plate Design**

Force plates vary slightly in structure and operation but the unifying design comprises a rigid top plate mounted on four support pillars. Each pillar consists of a series of force transducers providing three orthogonal components of force, which being at known separations, allows moments about the three principal axes to be determined. Despite its very extensive use in biomechanics research, papers on the calibration and specification of force plates are rare. Exceptions include Antonsson and Mann (1985); Kerwin and Chapman, (1988a, b); Bobbert and Schamhardt (1990); Hall, Fleming, Dolan, Millbank and Paul (1996). Hall et al. (1996) reported a series of methods for calibrating a force plate in its normal operating position. These tests comprised dead weight loading up to 1250 N, accurate vertical point loading via a ball bearing at the end of a shaft in a vertical ball race to enable accurate positioning over a prescribed grid to create moments of ±50 N.m. Horizontal forces were applied via pulleys enabling forces and moments to be applied accurately up to ±500 N and ±50 N.m respectively. A 6 x 6 cross-sensitivity matrix was calculated enabling the influence of orthogonal forces on the remaining pairs to be quantified. A particular point made by the authors was that the manufacturer's calibration figures refer to the plate alone whereas the calibration procedure described and recommended applied to the plate in situ and includes the mounting, amplifiers and recording systems. Bobbert and Schamhardt (1990) examined point of force application and showed it to be less accurate than might be expected from the Manufacturer's (Kistler Instruments) specifications. They were measuring a relatively large plate (0.90 m x 0.60 m) and found that the errors were only outside the expected range when dynamic forces were applied in the corners of the plate, beyond the perimeter of the load cells.

**Frequency Content of Movement**

Antonsson and Mann (1985), when investigating the frequency content of walking gait, examined the resonance of the force plate using the impact created by dropping a ball bearing
from a height of 200 mm onto the centre of the plate and measuring the resulting time domain signal at 2.5 kHz. They also used a Fast Fourier Transform (FFT) to convert the data into the frequency domain and concluded that the natural frequency of the unloaded plate in situ was about 700 Hz. They repeated the test with a 70 kg subject on the plate and found the resonant frequency to lie between 600 Hz and 800 Hz. In addition they applied a 30 Hz sine wave signal to the sampling equipment and applied the same FFT to inspect the captured signal in the frequency domain and in so doing checked the data transformation. They showed that the natural frequency of the plate was well above the expected maximum frequency of gait. Antonsson and Mann (1985) concluded that, with the measuring system they were using, the signal to noise ratio was appropriate for the task.

There have been very few reports on the frequency content of human movement. Alexander and Jayes (1983) reported a Fourier analysis of gait and showed that very few harmonics were required to reconstruct the main features of the walking force time trace. However, impact transients would be lost by the technique they reported. They removed the discontinuities at impact and toe-off by reflecting and rotating the force traces to produce continuous wave forms. Schneider and Chao (1983) reported a Fourier analysis of ground reaction forces in normal subjects and patients with knee joint disease. They found that in general up to the first four Fourier coefficients with the constant term were required to represent the main features of the ground reaction forces in walking. They also quantified "individual", "typical" and "general" patterns as those created during a single trial, a mean for a single subject over a series of trials and the mean of all trials for all subjects for either a normal or a patient group. Reflecting force traces, similar to those suggested by Alexander and Jayes (1983), were used but only when reporting "general" patterns. Schneider and Chao (1983) showed that the highest harmonics were associated with the medial lateral forces and the lowest with the vertical forces. They established $\lambda$ levels of 0.75, 0.90 and 0.95 representing the level of agreement between the reconstructed and the originally recorded force traces where a $\lambda$ level of 1.0 indicated an perfect match. They advised against using the lowest level of agreement (0.75), other than for modelling applications were a general pattern match only was required, and suggested 0.95 as the minimum $\lambda$ level for individual trial comparisons. The observations concerning the frequency content were somewhat different to those reported by Baumann, Procter and Klossner (1985), since for individual trials, Schneider and Chao (1983) reported higher frequencies in the force data for the non-affected leg than the diseased leg. However, when the data for a typical trial were considered, the findings were in agreement with Baumann et al. (1985). They agreed that in pathological gait there were higher frequency components than in normal gait. Kerwin and Chapman (1988b) reported the frequency content of hurdling and running. The two activities were studied in different locations so that, although the force plate was the same, the mountings were different. A modal analysis of the force plate in two locations was undertaken. The hurdling data were collected at an outdoor mounting site designed to the manufacturer's
(Kistler UK) specifications. The resonant frequency was found to be in excess of 750 Hz. The running data were collected in the laboratory with the force plate mounted on a purpose built solid steel base, the resonance of which was found to be close to 500 Hz. Fourier analysis of the hurdling and running data revealed that almost all the signal energy was contained in the low frequencies. Even the hurdling data, for an international athlete wearing spiked running shoes and landing from a hurdle clearance on the textured Athleprene track surface covering the force plate, had the majority of the signal energy below 100 Hz. The corresponding maximum frequency of interest for the same subject wearing training shoes for the running trials was 60 Hz. This paper presented a series of mode shapes for the force plate on its two mountings. It also showed that higher frequencies were contained in the medio-lateral forces than in the vertical forces and thus matched the similar observation by Schneider and Chao (1983) in respect to walking gait. The resonances for the various rocking and bending modes indicated some frequencies well above the solid body vertical motion mode shape of 525 Hz, with at least two bending mode shapes in excess of 900 Hz. The sampling rate for the force data capture had therefore been set to 2.5 kHz to avoid aliasing of identified high frequency components within the primary recording instrument.

**Sampling Frequency**

Sampling rate is of similar importance when selecting a visual image recording and analysis system. However, direct extrapolation from the frequency profiles of force plate data records to film sampling rates is not straightforward. Force records contain the full spectrum of frequency components associated with a dynamic human body in motion. In contrast, visual analysis techniques normally use rigid segmental body representations with compound segments (e.g., HAT: Head, Neck, arms and Trunk forming a single segment). Thus wobbling mass motions of soft tissues and transients at impact can not be readily identified with a visual recording system. The main problem is the high level of noise in the digitised position data and the requirement to low-pass filter these data prior to differentiation. Antonsson and Mann (1985) when studying walking found that frequencies with amplitudes greater than 5% of the amplitude of the fundamental frequency were all below 10 Hz, and that all frequencies below 1% of the fundamental were contained within the first 50 Hz. As a result they were able to show that 99% of the signal power was below 15 Hz and advised that kinematic systems used for recording normal gait should maintain "positional fidelity" up to 15 Hz. The Nyquist limit would indicate a minimum sampling frequency of 30 Hz, but this would only provide two data points per cycle and so a 300 Hz sampling rate was recommended giving 20 points per cycle. This is well above the specification advised by Winter, Sidwall and Hobson (1974), who showed that almost all the signal power was below the 7th Harmonic, (<6 Hz), and therefore justified using a video based sampling system which would be limited to 50 hz or 60 Hz. Baumann et al. (1985) identified frequency components up to 22 Hz in pathological gait and advised against limiting sampling
frequencies to 50 Hz. Lanshammer (1981) showed that sampling frequencies as high as 195 Hz were required to accurately record gait if second derivatives were to be maintained to a high level of accuracy. Lanshammer (1982) reported an elegant series of equations to enable the precision limits for derivatives to be determined.

Cinefilm and Video Recording

Cinefilm has been the primary medium for studying human movement since the pioneering work of Muybridge and Marey in the late 19th Century. Elftman (1939, 1940), Eberhart, (1947) cited by Paul in Cappozzo et al. (1992), and Bresler and Frankel (1950), continued this tradition, but the application of cinematography to the analysis of sporting actions, heralded by Cureton (1939), and reinforced by others (Glassow, 1952; Hubbard, 1959; Noss, 1967, cited by Doolittle, 1971) was brought into more common usage by Plagenhoef (1968). Cinefilm remains the most popular visual recording system where frame rates in excess of 50 Hz are required. However, over the past twenty years video has begun to rival cinefilm as a major recording system for sports biomechanical analyses. Video was given an additional boost when the International Olympic Committee's Scientific and Medical Commission of the 1992 Barcelona Olympic Games stated that preference would be given to biomechanical research projects using video. The early vidicon tube based video cameras using long persistence tubes suffered from after image effects making images of movement blurred and indistinct. The introduction of charge couple devices (CCD) changed the scope of video technology so that very short duration exposure times and the low light sensitivity offered by modern CCD's enabled high quality images of fast moving actions to be recorded. However, the standard sampling frequency of 50 Hz (PAL) or 60 Hz (NTSC) video equipment has limited its dynamic range. High speed video systems offering sampling rates of 200 Hz, 400 Hz and 1000 Hz by manufacturers NAC and Kodak do exist, but the increase in field numbers, within what is a restricted bandwidth, inevitably reduces line resolution and hence image clarity.

A number of studies have been conducted to evaluate the strengths and weaknesses of video in comparison with the well established cinefilm recording medium, (Kennedy, Wright and Smith, 1989; Kerwin and Templeton, 1991; Angulo and Dapena, 1992; Kerwin and Challis, 1994). Video accuracy values, expressed as a percentage of the field of view, have varied from 0.8% (Shapiro et al. 1987) to 0.3% (Angulo and Dapena, 1992) and Kennedy et al. (1989). The corresponding cinefilm estimates averaged 0.2%, (Wood and Marshall, 1986; Hatze, 1988; Kennedy et al. 1979; Angulo and Dapena, 1992). These studies have been either two-dimensional (Shapiro et al. 1987; Kerwin and Challis, 1994) or three-dimensional (Kennedy et al. 1989; Angulo and Dapena, 1992), and the fields of view studied have ranged from 2 m to 10 m, making direct comparisons difficult. However, image resolution has commonly been identified as a limiting factor on accuracy for data collected using video and
typically the errors associated with video image data have been between 50% and 300% greater than the corresponding values expressed for cinefilm. Recent developments in computer imaging of video fields with image zooming capabilities, have reduced the discrepancies between cinefilm and video, (Kerwin and Challis, 1994). In a recent study, Tan, Kerwin and Yeadon (1995) demonstrated that the addition of a sub-pixel cursor (Kerwin, 1995) has eradicated the differences in accuracy between 16 mm cinefilm and Hi8 video recording systems. A 10 m field of view, which is common in sports biomechanics, was used in this study. It is therefore clear that video recording is now spatially accurate enough for photogrammetric measurement, although the sampling frequency of standard video recording systems limits its time resolution. The publication dates of the comparison papers indicates that the technology which facilitates these improvements has only been available within the very recent past.

Data Processing

The processing of image data has varied. Data "smoothing" has been accomplished using graphical techniques (Smith 1975), cubic splines (Hudson, 1986) and most commonly, using a 4th order zero lag Butterworth filter (eg. Ingen Schenau et al. 1985; Soest et al. 1985; Bobbert et al. 1986, 1987a, 1987b, 1988). The selection of the cut-off frequency used in the Butterworth routines has varied from 4 Hz used by Hubley (1985), 5 Hz used by Hubley and Wells (1983), 10 Hz by Fukashiro et al. (1993) and 16 Hz by Bobbert et al. (1986). The latter authors did however, report that the difference between 10 Hz and 16 Hz was small, and Fukashiro et al. (1993) stated that there were few high frequency components in the data they were analysing without actually reporting the frequency profiles of the data. The errors associated with failing to smooth positional data prior to differentiation are widely accepted and commonly acknowledged. Techniques for smoothing and differentiating movement data are varied but have been thoroughly investigated (Winter, Sidwall and Hobson, 1974; Pezzack, Norman and Winter, 1977; Soudan and Dierckx, 1979; Wood and Jennings, 1979; Lees, 1980; Hatze, 1981; Lanshammer, 1981, 1982; Woltring, 1986; Challis and Kerwin, 1988; Kerwin and Challis, 1989). Woltring (1992), in Cappozzo, Marchetti and Tosi (1992), stated

*Generally, movement data will have a low-pass nature, with additive, wide-band noise, and this is the appropriate situation for a variety of low-pass filtering and differentiation procedures. Woltring 1992, p212.*

A popular and commonly used combination of low-pass filtering and differentiation for movement data is the Butterworth filter followed by direct difference procedures which are based on Taylor series approximations. Miller and Nelson (1973) reported a series of first and second central difference procedures for determining velocity and acceleration from
displacement time data. Lanczos (1967) described a series of five, seven and nine point procedures for achieving the same effect but with additional amounts of smoothing as the number of points in the procedure increased. These difference techniques have been used by a large number of authors (Lees, 1980; Bobbert et al. 1986, 1987a, 1987b, 1988; Winter, 1980, 1983; Ingen Schenau, Bobbert, Huijing and Woittiez, 1985; Soest et al. 1985; Kerwin, 1988, 1992; Kerwin and Hamilton, 1988; Kerwin and Sprunt, 1989). The sensitivity of the selection of the cut-off frequency has been criticised as a weakness of the Butterworth filtering process, and the range of cut-off frequencies used in relation to filmed analyses of jumping supports this observation. Splines have been proposed as an alternative solution. Cubic splines have been used (McLaughlin, Dillman and Lardner, 1977; Zernicke, Caldwell and Roberts, 1976) but these have limitations, particularly when trying to determine second derivatives. The Reinsh spline (1967), was a more robust piecewise method which has become popular as an interpolating routine, particularly where data from one timebase are to be converted to another. This is useful when synchronisation between data recorded using separate instruments. Wood and Jennings (1979) proposed using quintic splines, but required the user to input an 's' value to tune the spline depending upon the error content in the data. Like the Butterworth, this is subject to interpretation and skill on the part of the operator if the best results are to be obtained. Woltring's (1986) generalised cross validated spline (GCVS) solved the latter problem by automatically selecting the tightness of the spline fit based on the information in the raw data. This procedure allows the user to select the order of the spline with quintic being a popular choice for smoothing and differentiating human movement data. This software was computationally demanding when it was first introduced, but with the dramatic increase in computing power, currently running at a doubling of speed and a halving in price every 18 months, this is no longer a limitation. Hatze (1981) truncated Fourier series approach to data smoothing is an attractive alternative and is automatic in the sense that it automatically selects the appropriate cut-off frequency. By transforming the position data into the Frequency domain, truncating the series at a suitable point and then by using an inverse transformation, the data are returned to the time domain. It is therefore possible to remove unwanted high frequency components or noise. Detrending of data is sometimes required and some problems can occur when dealing with discontinuities, but these are common to all position based motion data where impacts are involved. All techniques appear to have weaknesses, but with careful selection and use, all also appear to offer some strengths and benefits.

The process of numerical integration has been relied on heavily by investigators such as Davies, Cavagna, Bosco, Komi and Luhtanen when comparing different styles of jumping. Only one paper, published very recently, has commented on errors associated with the process of integration. Anderson and Pandy (1993) reported an error in the second integral, (ie. displacement of the mass centre) which accumulated at a rate of 1.5 cm.s⁻¹. The authors attributed this error to the inability of the force plate to follow precisely the rapid changes in the
forces applied. The effect of this error on jump heights, determined solely from force plate data, is therefore dependent on the duration of the data capture period. Anderson and Pandy (1993) suggested an error of ±2 cm for a counter movement jump and ±6 cm for a squat jump. The implications for all previous studies, which have shown small differences between height jumped using these two techniques and which take varying amounts of time to execute, are significant. The very large error associated with the squat jump arose because Anderson and Pandy (1993) started the integration process with the subject in erect standing prior to squatting and coming to rest for two seconds prior to jumping. This meant that the total data capture time was close to four seconds, although the jump time was only half a second. However, the error introduced by the integration process in each jump style, even if the squat delay time is removed, is in the region of 5% to 6% of jump height which is also the same magnitude as the differences in height jumped reported by several authors (Komi et al. 1978a, 1978b; Hubley and Wells, 1983). Studies which have shown these differences have attributed the greater jump height in the counter movement style of jumping to the enhanced storage and utilisation of elastic energy. They have also attributed greater jumping performances, in rebounds following drop landings, to increased the stretch loading on the extensor musculo-tendon complexes in the lower limbs, (eg. Asmussen and Bonde Peterson 1974a). Anderson and Pandy (1993) used combined modelling and experimental techniques to examine the differences between counter movement and squat jumping performances and showed that jump height remained almost the same for both techniques. They concluded that elastic energy storage and utilisation enhanced jumping efficiency much more than overall jumping height.

The identification of joint centre markers when digitising film images can produce noise in the coordinate data which is systematic and random. The random errors can be minimised by repeated digitisations of the film sequence (eg. Atha, Yeadon, Sandover and Parsons, 1985) or by low-pass filtering (eg. Pezzack et al. 1977). Systematic errors are associated with marker location and skin movement. Errors due to skin marker movement can be of the order of 10 to 20 mm in 3-D, (Cappozzo, Catani and Leardini, 1993). The problem arises because skin moves over a joint as the joint angle varies. If the joint centres are estimated from the anatomical orientation of the limbs, then the joint centres can be estimated without reference to skin markers providing that the operator is sufficiently experienced. Almost all jumping studies have relied on 2-D cinefilm data and so more sophisticated 3-D techniques are not applicable. Bobbert et al. (1986), for example, described the use of markers located on the foot, ankle, hip and neck. Joint angle changes in vertical jumping are generally not large and so the errors associated with skin movement, and hence the incorrect location of joint centres, are not likely to be large. The effects of misjudging the location of joint centres and of using single markers on the trunk, neck or head to represent the orientation of the trunk are factors which need to be considered in film analyses in which joint angles and joint angular velocities are important.
Data Synchronisation

When cinefilm image data and force data are to be collected simultaneously, some consideration of data synchronisation is essential. Errors introduced through poor synchronisation can be significant. A number of devices have been proposed for use in film based studies in which more than one camera has been used. Synchronisation may be effected by interpolating the separately recorded data sets over the same time base. Walton (1981) used a timer in view of both cameras to establish frame times and then linearly interpolated the data of the faster camera over the time base of the slower. Dapena (1979) used a timer to obtain start and end times for each activity and assumed that the framing rate was constant between these end points. The resulting frame times for each camera were matched using an interpolating cubic spline. If no timing device is present in the fields of view of the cameras, the digitised data itself can be used. Yeadon (1989) synchronised two sets of 3D cinefilm data of ski jumping at takeoff by assuming that the mass centre of the athlete's body was in the vertical plane which bisected the "in-run". At landing no such assumption was made, but it was necessary for the velocity vector of the ski jumper to make a sufficiently large angle with the plane defined by the positions of the athlete and cameras. This latter form of synchronisation is particularly useful when data are collected in an environment where little or no control can be exerted by the experimenter, for example at major competitions.

The primary problem when linking cinefilm with itself or with force plate data is that film and digitised analog wave forms produce discrete data values. These values although recorded in parallel may be logged at slightly different moments in time. If film images are sampled at 50 Hz, errors in time synchronisation of up to half a frame interval (10 milliseconds) are possible. Recently a new device for improving synchronisation between film and analog data was proposed by Rome (1995). He suggested that irrespective of the film framing rate and "take" duration, providing that the analog sampling rate was sufficiently high, the errors in synchronisation between the film images and the biological data could be as low as ±0.2 ms throughout the action. Other methods which have been employed in the past include increasing the film framing rate, directly synchronising the analog data capture with the shutter pulse from a cinefilm camera, and ADC logging the pulses from an internal timing light unit within a cinefilm camera.

Body Segment Inertia Parameters

Body segment inertia parameters are important to quantify in biomechanical analysis, but are difficult to select for individual subjects. The normal values required for inverse dynamic analyses of human movement include segmental masses, centre of mass locations and moments of inertia about three principal axes. When 2D analyses are conducted, only moments of inertia
about transverse axes are required. A range of inertia data sets have been used in studying human jumping. The Amsterdam based group including Bobbert, Ingen Schenau and Soest in their many studies of coordination in, and modelling of jumping, have used inertia data from Clauer, McConville and Young (1969). Fukashira et al. (1983, 1993) and Miller and East, (1976) used the classic data from Dempster (1955) whereas Hudson (1986) used the mathematical model of Hanavan (1964) to generate inertia data for her analyses. Smith (1972, 1975b) used Whitsett's (1963) model based inertia data. Kerwin and Hamilton (1988) compared the effects of using different inertia data sets on the moments generated about the knees and hips in kicking. They showed that there were little differences when the established cadaver, and regression, based inertia data sets (Dempster, 1955; Clauer et al. 1969; Winter, 1979) were used. However, there was a marked difference (>10%) between the moments and work produced at the hip and knee when the body segment inertia parameters produced by Zatsiorsky and Seluanov (1983) were used in place of any of the traditional sets. As the Zatsiorsky and Seluanov (1983) values were based on gamma scans of live young physical education students, and the majority of the previously listed values were based wholly or partly on cadaver studies of elderly and derelict males, it is perhaps not too surprising that the two groups were different. Improved mathematical modelling procedures have been developed using photographic images (Jensen, 1978) or anthropometric measures (Hatze, 1980; Yeadon, 1990b). These can be customised to individual subjects, but in the cases where anthropometric measurements are required, subject cooperation is necessary and time consuming. The cadaver based studies provided data which were directly measured from the body segments and hence were likely to be accurate. The subjects however, where not representative of the young athletic population generally studied in sports biomechanics. The mathematical modelling methods proposed by Jensen, Hatze and Yeadon, although customised to specialist populations, are virtually impossible to evaluate. Some confidence can be gained from Yeadon's modelling methods (1990b), in the sense that anthropometric measures taken from the body, but not including body mass, enable body mass to be predicted to an accuracy of between one and two percent. Also using Yeadon's (1990b) model, total angular momentum of the human body in flight which should be constant, has been shown to have minimal variation around a constant value (Kerwin, Yeadon and Lee 1990; Yeadon, Lee and Kerwin, 1990). This observation indicates that the moment of inertia and mass centre locations, although not individually verifiable, do nevertheless, provide a good overall representation of the inertia characteristics of the subjects studied. The introduction of computerised tomography (CT), (eg. Huang and Wu, 1976) and more recently magnetic resonance imaging (MRI), (eg. Martin, Mungiole, Marzke and Longhill, 1989; Mungiole and Martin, 1990) has prompted a renewed interest in body segment inertia parameter determination. Also the original linear regression techniques, developed by Clauser et al. (1969), have been considerably revised. The work of Chandler, Clauser, McConville, Reynolds and Young (1975) has been revisited by Hinrichs (1985), and adapted for use with upper limb segments by Challis and Kerwin (1992). Non-linear techniques have been shown to
be superior to linear methods by Yeadon and Morlock (1989). Scaling of moments of inertia values derived from cadaver data has been proposed by Forwood, Neal and Wilson (1985). The latest developments in digital imaging used in the "Visible Human Project", now available on the World Wide Web, indicate that body segment inertia parameters, determined at least for a single male and a single female subject, will be verifiable in the near future. The inertia characteristics of special populations, like elite gymnasts or athletes, and children are not well represented in the research literature. Ackland, Blanksby and Bloomfield (1994) reported data on thirteen adolescent boys over a two year period. Jensen's (1976) photographic technique was developed specifically for and has been used in the study of inertia changes in boys passing through puberty. Yeadon's (1990b) model was originally developed for use in his PhD study of twisting somersaults by elite trampolinists and has been used more recently for analysing gymnasts performing a variety of twisting somersault skills, (Yeadon et al. 1990; Yeadon, 1994). In the absence of customised inertia parameters, some comparison of the influence of different inertia data sets is an alternative. A sensitivity analysis to determine the influence of the inertia data on the resulting inverse dynamic analyses is therefore a possible option. It was decided that comparing the output from the analyses, using at least two inertia data sets, was advisable and that one of the chosen data sets should be that of Zatsiorsky and Seluanov (1983).

Analysis Systems used in the Study of Vertical Jumping

A small number of vertical jumping studies have been conducted without the use of force plates. Bosco, Luhtanen and Komi (1983) used an electronic clock and timing mat to record flight times in a repeated jumping test of energy expenditure. Martin and Stull (1969) used goniometers to set knee angles and then simple linear measurements from a jump board to investigate the influence of knee angles and foot spacings in vertical jump height. Hubley (1985) combined 50 Hz cinefilm data with EMG of five muscle groups to investigate kinematic and electrical activity patterns in a variety of activities including vertical jumping. However, experimental studies of vertical jumping increased in number once force plates became more readily available, (Davies and Rennie, 1969; Davies 1971; Cavagna, 1970; Asmussen and Bonde-Peterson, 1974a, b; Alexander and Vernon, 1975; Bosco and Komi, 1978a, b, 1979a, 1980; Komi and Bosco, 1978a, b; Aura and Viitasalo, 1989). Most of the more detailed biomechanical studies of vertical jumping have combined visual images with force plate data. Despré (1976) used a Graph-Check sequence camera to synchronise a series of eight still pictures with force data from a custom built strain gauged plate. This study also included electrogoniometer and accelerometer data. Most of the other studies have used cinefilm (Smith, Dowson, Adamson and Wright, 1974; Smith, 1975b; Miller and East, 1976; Hay, Dapena, Wilson, Andrews and Woodworth, 1978; Hubley and Wells, 1983; Hudson and Owen, 1985; Ingen Schenau, Bobbert, Huijing and Woitiez, 1985; Hudson 1986; Bobbert et al. 1986, 1987a, b, c, 1988; Fujii and Moriwaki, 1992; Fukashiro et al. 1992; Soest et al. 1985, 1993;
Prilutsky and Zatsiorsky, 1994). The latter group have all used frame rates of between 50 Hz and 100 Hz and most have used intermittent action cameras (eg. Locam). Smith (1975b) was unusual in using framing rates between 64 and 500 fps. The majority of these studies have been two-dimensional with simple linear scaling based on the assumption that the vertical jumping action has sagittal plane symmetry. Automatic kinematic data acquisition systems have been used to study vertical jumping. Pandy and Zajac (1991) sampled data at 312 Hz using a Selspot II system, and Anderson and Pandy (1993) used a Motion Analysis™ system to sample kinematic data at 60 Hz. Both studies used planar analysis to generate data for evaluating forward dynamics models of jumping. Almost all the studies have used Kistler force plates (models 9261 or 9281). The exceptions are the studies by Prilutsky and Zatsiorsky (1994) who used a PD3-A Visti, from the former Soviet Union, and the study by Hubley and Wells (1983) who used an AMTI force plate. Few researchers have reported the natural frequency of the force plate systems used. Asmussen and Bonde-Peterson (1974a, 1974b), reporting approximately 50 Hz, and Pandy and Zajac (1991), quoting 500 Hz, are the exceptions. Sampling methods and sampling frequencies have also varied considerably. Early studies used ultra-violet recorders (Alexander and Vernon, 1975); storage oscilloscopes (Miller and East, 1976); or transient recorders (Bosco and Komi, 1978a, b) with data extracted at time intervals of 0.02 s to 0.03 s (approximately 50 Hz). Most other studies have used computerised data capture systems with sampling frequencies from 500 Hz (Bobbert et al. 1986, 1987a, b, c, 1988) to 1000 Hz (Pandy and Zajac, 1991; Anderson and Pandy, 1993). The exception is the French study by Cochard and Junqua (1986), where a sampling frequency of 10 kHz was used. The other referenced studies, reported little or no information on the precise nature of the force plate recording system, the natural frequency of the equipment used or the data sampling methods employed. The comment by Desiprés (1976) when referring to an unpublished PhD thesis by Gerrish from 1934 commented:

*The values (for takeoff velocities in vertical jumping) were high and it must be taken into account that this research project was done many years ago when instrumentation was perhaps not as sophisticated as today.*

Desiprés (1976), p. 76.

A further twenty years of equipment evolution has occurred since this statement was made. When added to the observations about lack of detail relating to methods of data acquisition, the importance of attending to these topics in future studies is highlighted. Also many of the findings of vertical jumping studies from the 1970's and 1980's should be interpreted with care.


2:3 MODELLING JUMPING

Introduction

Most biomechanical models are mathematical representations of real systems (Yeadon and Challis, 1994). Models can be used to conduct forward dynamics and inverse dynamics analyses of motion (eg. Zajac, 1993). In forward dynamics, or simulation modelling, the inputs are forces acting on a system and the outputs are kinematic descriptions of the motion. In inverse dynamics, the process is reversed with kinematic data describing a motion being the inputs and the applied forces and moments being the outputs. Both forms of modelling have been used in human biomechanics. The primary focus in this section is a consideration of the moments acting about joints in jumping and landing. Within it there is also a consideration of segmental energy analyses which contrasts the variety of approaches that have been attempted and the conflicting evidence that has been produced.

Inverse dynamics

Inverse dynamics is a process of calculation. It is based on the fact that knowledge of the motion of a body enables the forces that cause the motion to be determined. When analysing human movement, body segment inertia parameters and segmental kinematics are required. From these two sets of data it is possible to calculate the forces acting to move the system. If a single external force is also known, for example when using a force plate, then there is redundancy in the data which improves the accuracy of the calculated values. There are three outputs from inverse dynamics; resultant joint forces, muscle moments and joint power. Under the traditional link modelling representation of the human body, introduced by Dempster (1955), the inertia characteristics are regarded as constants. That is the mass, centre of mass location and the three principal moments of inertia of each segment, are treated as fixed values throughout a motion. The joints are regarded as simple frictionless hinges or pins. This simplification of the body enables the mathematics to be reduced to a manageable level whilst still representing the main actions and motions of the limbs. More sophisticated models of the body segments with bendable bones and wobbling soft tissue masses have been used in biomechanics (eg. Denoth et al. 1984; Gruber, 1992) but the majority of studies of human motion in sport have used a rigid link segmental model (eg. Elftman, 1940; Winter, 1983; Robertson and Mosher, 1985; Ingen Schenau et al, 1985; Bobbert et al. 1987a, b; Buckley and Kerwin, 1988; Gervais, 1993; Sanders et al. 1991; McNitt-Gray, 1993). The resultant joint moments are caused by the force due to the muscles, and by the passive deformations of any tissues which may cross or surround the joint. It is common to assume that the articular contact forces act through a single point only, which is the pre-selected joint centre. This makes the moment arm of this force about the joint centre zero, and the contribution to the resultant joint
moment also equal to zero. If the ligament forces are ignored, the resultant joint moment is assumed to be caused entirely by the muscles, in which case it can be called the muscle moment. Such assumptions are made in this study. The muscle moment only gives the net effect of all the muscle forces, with co-contraction of the muscles crossing a joint meaning that it is difficult to infer the forces being produced by a functional grouping of muscles. Andrews (1983) provided a useful description of the joint and moment determinations used in inverse dynamic analysis and clarified the reasons why the net muscle moment about a joint was used as the best indicator of muscular effort. He also showed that if the "distribution problem" had been solved, that is if the joint geometry and individual muscle forces had been identified, then it was not necessary to also state the muscle moments. If a forward dynamics modelling approach is adopted then this would be the case. Invasive experimental techniques (eg. Fukashira et al. 1993) provide alternative ways of determining individual muscle force estimates, but these are not applicable in normal inverse dynamic analyses. Fukashira et al. (1993) reported "in vivo" measurements of internal forces. A buckle transducer was fitted to the Achilles tendon of a single male volunteer who performed a series of squat and counter movement jumps, and repetitive hopping on the spot on a force plate. He kept his hands on his hips throughout, in the manner described by Komi and Bosco (1978a). In general Fukashira et al. (1993) found that the Achilles tendon force was approximately twice the ground reaction force and that the level of agreement between the directly measured and estimated values was poorest in the early plantar flexion phase with errors of 40% in the squat and counter movement jumps and 8% in the submaximal hopping task. In all cases the values estimated using inverse dynamics were higher than those measured directly. Some knowledge of forces and moments has also been gained from animal based studies, (eg. Alexander and Vernon, 1975b). The major advantage offered by animal studies is that a detailed anatomical analysis can be carried out at the end of the experiment. Although this can be challenged on ethical grounds, the fact that segmental inertia, muscle cross-sectional area, bone geometry and hence muscle moment arm lengths can be determined makes this form of study ideally suited to investigations of the mechanics of motion.

By combining the muscle moments acting about a joint with the joint kinematics, in particular the angular velocity of the joint, it is possible to determine the muscle moment power at that joint. This provides a very useful scalar biomechanical measure of muscular effort (muscle moment power), whether used as an instantaneous value or as an average value over a time interval. It is common for the muscle moment power at a joint to be integrated over time to determine the contribution made by the joint musculature to the total action, (eg. Winter, 1983; Bobbert et al. 1987a, b; McNitt-Gray, 1993). Bobbert, et al. (1987a, b) reported two studies on drop jumping. In the first, ten subjects performed a traditional counter movement vertical jump and two types of drop jumps from a height of 20 cm. In one, the subjects were asked to perform a 'counter movement drop jump'. That is they dropped into a deep squat and took time to reverse the downward to upward motion. In the second or 'bounce drop jump' the subjects were
encouraged to reverse the downward to upward motion as quickly as possible. The push off phase, which was defined as starting at the lowest point of the mass centre's displacement, was analysed and kinematic data revealed that there was a mean difference of vertical mass centre displacement of 12 cm between the two drop jumps and that the mass centre started from 12 cm lower still in the traditional counter movement jump push off phase. They found that the moments and power output at the ankle and knee joints were greatest in the bounce drop jump technique. Interestingly the greatest hip moments occurred in the counter movement jump. They did warn however, about the caution that needs to be exercised when considering net moments, since as Andrews (1983) pointed out, the activity of any antagonist muscle groups is ignored in the traditional inverse dynamic analysis. They also reported that the duration of the action was longest for the counter movement jump, and shortest for the bounce drop jump, but that the takeoff velocities for the three techniques were very similar. Both drop jumps did, however, produce higher takeoff velocities than the counter movement jump (p<0.05). The authors concluded that the bounce drop jump technique was more likely to produce better mechanical output at the knee extensors and ankle plantar flexors and advised that the precise nature of the drop jump action should be controlled to encourage the 'bounce' style. In the follow up paper to this study, Bobbert et al. (1987b) extended the 'bounce drop jump' to study the influence of increasing the height of dropping (20 cm, 40 cm and 60 cm) and thereby increasing the stretch loading on the extensor muscle groups of the lower limbs. Using similar calculations to those in part I of the study, Bobbert et al. (1987a), found no differences in joint power output for the push off phases from the three drop heights, although the ankle moments and powers were slightly greater when dropping from 40 cm than either of the other two heights. They also reported resultant joint force data to highlight the transient peak values encountered as the heels struck the force plate after dropping from 60 cm which did not occur under the other two drop height conditions. They warned against using dropping heights in excess of 40 cm in training to reduce the likelihood of injury.

Quasi-static determination of muscle moments

Determination of muscle moments using inverse dynamics is clearly relevant when studying dynamic activities like walking, running, jumping and landing. However, it is surprising that quasi-static approximation techniques have been shown to be a useful and much simpler method of achieving the same end. What is not so clear is the extent to which the necessary approximations associated with the use of the quasi-static methods influence the values obtained. The quasi-static approximation method requires that each moment in time within a movement is treated as static by ignoring segmental weight and inertia forces. The direction and magnitude of the ground reaction force vector relative to the prescribed joint centre is then regarded as the only force acting and an estimate of the opposing muscular moment necessary to maintain the system in equilibrium is calculated. The product of the perpendicular distance
between the joint centre and the force vector is determined and equated with the opposing muscle moment required to balance the calculated ground reaction moment. Winter (1990) has strongly criticised the quasi-static method showing that, if extended beyond the joints of the lower limbs up into the trunk, the moments about the neck would be so enormous as to have no meaning. Alexander and Vernon (1975) showed that the level of agreement between planar ankle and knee moments in vertical jumping, determined by inverse dynamic and quasi-static methods, was very good with a root mean square difference of approximately 2% and 7% respectively. Lanshammer (1993) described a system called VIFDIG which used quasi-static approximations of joint moments in walking. He had developed the system for clinical use to enable quick (approximately 5 minutes per walking step) estimates of muscle moments in twin planar views of walking gait to be obtained from standard video images. Superimposing a computer controlled cursor onto a stored video image enabled coordinate data to be obtained. If a video image in which a force vector visualisation was present (eg. VIFOR, Lanshammer, 1988) digitising the ankle, knee, hip and two ends of the force vector enabled a reasonable estimate of the moments about the lower limb joints to be determined. He admitted that the video data were too noisy to obtain acceleration data from but claimed a 5-10 N.m error in the estimated moments using this quasi-static approximation. He had made over 1000 patient measurements and stated that the moment errors were largest for the hip and smallest for the ankle. Cappozzo, Leo and Cortesi (1980) used the quasi-static technique for predicting of knee moments on the prosthetic side in A/K amputees in walking, having already evaluated the technique to show that errors of 10% were anticipated. Wells (1981) also used inverse dynamic and quasi-static methods to evaluate resultant moments generated at the hip, knee and ankle during walking. He referred to the method as a projection of the ground reaction force and reported "projection errors" as the difference between the approximate technique and the values obtained by inverse dynamics. Typically the errors, expressed as a percentage of the range of joints moments, were about 1% at the ankle rising to 30% at the hip. Wells (1981) cited a study reported by Pezzack and Norman at the 1980 International Seminar on Biomechanics which also produced similar errors. The main conclusion from Wells (1981) paper was that the quasi-static technique produced estimates of ankle moments which were negligibly different to those determined by inverse dynamics, but that the differences at the knee and hip were of larger magnitude. More importantly, the largest errors occurred close to heel contact and push off and often with the opposite polarity to the values determined by inverse dynamics. Clearly these could have serious clinical implications and so should be treated with caution. Kerwin (1988) compared quasi-static and inverse dynamic estimates of moments at the ankle, knee and hip for the stance phase in walking and running and found differences of 2%, 11% and 25% for walking at 1.53 m.s⁻¹ and <1%, 14% and 50% for running at 3.75 m.s⁻¹. There was also some evidence of reversal of polarity at foot contact and toe off in both walking and running.

Few examples of quasi-static approximations to moments in jumping activities have been
reported. In addition to the study by Alexander and Vernon (1975), Watkins and Nicol (1986) used quasi-static techniques to study ankle, knee and hip moments and muscle moment power contributions in jumping action in gymnastics. In particular, they analysed takeoff actions for the flic-flac or backward handspring, and in an earlier study for the backward somersault and flic-flac (Watkins and Nicol, 1985), but did not report any error estimates between their results and equivalent values using the more traditional inverse dynamics. Bogdanis (1990) completed a comparative study of the muscle moments in the standing backward handspring takeoff. He found that the approximated moment curves generally matched the shape and magnitude of the inverse dynamic moment curves although the percentage root mean square differences at the ankle and knee were 5% and 16% at the hip. (Bogdanis expressed the errors as percentages of the mean moment values rather than the moment ranges and so the values have been converted to match the other reported data).

The quasi-static technique is clearly convenient to use, and for certain joints, can produce realistic muscle moments values. No acceleration or inertia data are required, and so errors associated with differentiation of noisy displacement data or inappropriate segmental body segment inertia parameters are avoided. It is clear however, that the nature of the activity being analysed, and the selected joints, influence the magnitude and polarity of the moments and hence the size of the errors that can be expected. Squat jumping, counter movement jumping and rebound jumping are activities in which the alignment of the ankle, knee and hip joints can be considered to remain relatively close to the ground reaction force vector throughout the action and so it might be expected that the moments at the ankle and hip in particular could be expected to closely match with those calculated by inverse dynamics. The suitability of the quasi-static technique for muscle moment, and the associated muscle moment power, analyses should therefore be assessed for an activity before the technique is accepted or rejected. Alexander and Vernon (1975) drew force vectors onto prints made from 16 mm cinefilm images. Today, computerised force sampling with associated digitally stored video images improve the accuracy, speed and convenience of this form of analysis. The quasi-static technique for determining muscle moments is worth investigating in relation to human jumping, to ensure that the conclusions drawn agree with those generated using inverse dynamics. If this proves to be the case, then the quasi-static technique could be accepted as a technique for conducting routine muscle moment analyses. Also, using the quasi-statically determine muscle moments and providing that in addition to ankle, knee and hip joint centres, toes and shoulders are also digitised, it would be possible to calculate the relative angular velocity of the ankle, knee and hip joints and hence determine muscle moment power. This would provide a convenient and straightforward way of estimating joint power contributions in jumping and landing and hence via integration to determine the relative work or energy contributions by each of the joints of the lower limbs.
Segmental Energy Analysis

An alternative method for calculating energy in human movement is based on the analysis of segmental energy. This approach has been adopted in a range of biomechanical studies, and was summarised by Williams and Cavanagh (1983). Their paper focussed on mechanical work and efficiency measures in running, but the methods and associated problems remain the same for other activities including jumping. The paper by Williams and Cavanagh (1983) highlighted the variations in energy cost obtained when adopting different researchers' methods for studying middle distance running. Williams and Cavanagh (1983) used the same film, force plate and inertia data with a range of calculation procedures extracted from previous research and showed that the resulting power values, for running at 3.57 m.s⁻¹, ranged from 273 Watts to 1775 Watts depending on the assumptions employed. The methods ranged from point mass energy analyses to "pseudo-work" calculations, in which all energy exchanges were assumed to have a metabolic cost.

Motion of the mass centre alone has been used to estimate power in running (Cavagna et al. 1964; Fukunaga, 1978). However, as Smith (1975a) pointed out, using the centre of mass alone for determining kinetic energy was at best an approximate solution. He argued that it considered only the linear motion of the body mass centre, and hence ignored three of the four energy costs of human movement. Those were the work done to overcome internal and external resistances, and that required for limb accelerations. He demonstrated that, even using a simple four segment model of the human body performing a vertical drop landing, could result in a 9% under-estimate of total kinetic energy. When an activity requiring greater rotation was studied the difference increased. For a standing broad jump the discrepancy was 35%. Fenn (1930) and Cavagna and Kaneko (1977) also used the motion of the limbs relative to the mass centre, but as Smith (1975a) highlighted, this is unacceptable since the quantity being calculated is scalar. Smith's (1975a) algebraic treatment, succinctly destroyed this relative motion approach showing it to be true only under two specific conditions. One where all the segments were moving at a constant speed in the same direction, ie. when the relative segmental velocities were zero and the second when a segmental centre of mass was moving orthogonally to the whole body mass centre. Neither of these can be regarded as representative conditions of general human movement. Smith (1975a) concluded that segmental analysis which used absolute segmental positions and velocities was the only satisfactory way of dealing with the determination of mechanical energy.

Segmental energy analyses have ranged from a 'pseudo-work' approach described by Norman, Sharratt, Pezzack, and Noble (1976), in which no segmental energy transfer is permitted, to one in which complete energy transfer between all segments is allowed, (eg. Winter 1978). As a result, when the pseudo-work method has been used, every change in mechanical energy state produced a metabolic cost, and hence the calculated total energy expenditure was extremely
high. At the other end of the spectrum of energy exchange, the assumption that energy could be transferred freely from any segment of the body to any other segment, irrespective of their relative proximity, resulted in a low net metabolic energy cost. In an attempt to identify the key factors which influence the energy cost of running, Williams and Cavanagh (1983) varied the relative contributions in a systematic way. For example, the proportion of energy transfer allowed ranged from 0 to 0.63 with 0.18 and 0.32 in between. Elastic storage of energy ranged from 0 to 0.50 with 0.24 and 0.35 between. Passive musculo-skeletal resistance in the limbs ranged from 0.6 to 1.0 with 0.85 between and the relative metabolic cost of positive and negative work ranged from 1 to 5 with 2 and 3 between. They used data from a variety of research sources, for example the elastic energy fractions were based on the work of Cavagna et al. (1964, 1971), Asmussen and Bonde-Peterson, (1974b) and Thys et al. (1972), to identify realistic boundary conditions for each of the four variables.

Williams and Cavanagh (1983) found that variations in energy exchange conditions and relative positive to negative work ratios were more influential than either elastic energy or total cost of negative work. Indirect calorimetry, based on oxygen consumption data, enabled consistent values to be obtained for the energy cost of running, with a mean value of 898 Watts in the study. In this sense the denominator had not lead to extensive problems. However, the numerator in the efficiency equation, the mechanical energy output term, varied dramatically with the method of calculation and the assumptions employed to enable the complexity of the human system to be treated as a manageable mathematical model.

Bosco et al. (1987b), when studying the effect of pre-stretch on mechanical efficiency of human skeletal muscle included data from treadmill running and vertical jumping. Six male subjects, performed a 4.5 minute run at 3.33 m.s⁻¹ and two sets of one minute duration rhythmical vertical jumps, with and without rebounds. The oxygen cost of the three exercises and recovery periods were measured, and then the approximate mechanical work and efficiency for running was estimated using the methods of Cavagna and Kaneko (1977). Mechanical work during the jumping exercises was calculated using the area under the force time curve, but as in all previous papers by Bosco and Komi, the total area was not correctly represented. A small negative area at either end of the force time trace during the ground contact time has been ignored. The error involved is small, but would be more substantial at the take-off end where the gradient is shallower than at the impact landing. Total positive work performed was assumed to be that due to the rise in potential energy resulting from the movement of the jumper from the bottom of the squat to the top of the jump flight. Negative work was assumed to be identical in magnitude but opposite in direction. Expired air was collected before energetic cost and efficiency were calculated. Stored elastic energy was calculated from a simple spring mass formula and mechanical efficiency calculated using the methods of Alexander and Vernon (1975b). This approach is appealing in its simplicity, but can also be misleading for a number
of reasons, not least of which are those detailed by Smith (1975a). In addition, Miller and Nissen (1987) pointed out that in rebound jumping skills, like the takeoff for a running forward somersault, the knees continue to flex after the minimum point of negative vertical displacement of the subject's mass centre. Thus the bottom of the path of motion of the subject's centre of mass does not represent the change from eccentric to concentric contraction of the leg extensor muscles. Bosco et al. (1987b) did acknowledge that chemical energy was being expended to maintain the isometric contraction required at the bottom of the squat position for the no-rebound condition, (approximately a decoupling time of 0.5 seconds), and yet this part of the mechanical work was omitted. Also the use of simple spring mass model was an over-simplification, even in comparison to a simplified mass spring damper system more typical of the human system, (eg. Shorten, 1987; McMahon, 1984). With more extensive use of the force plate data, velocity characteristics of the motion were available and could have been included. Finally Bosco et al. (1987b) used a video camera to determine the motion of the jumper. This would be limited by the relatively low time resolution of standard video recordings and hence the accuracy of locating the division between the two phases of the motion from eccentric to concentric. Asmussen and Bonde-Peterson (1974a) calculated work and energy changes from a point mass model. The product of nominal drop height and subject weight were used to determine total negative energy. Positive energy was calculated from standing height of CM to maximum height of CM at the top of flight path. They then assumed that no elastic energy was stored in squat jump and therefore calculated the fractional contribution of elastic energy by finding the difference in positive energy for each jump relative to positive energy for the squat jump and expressed this as a percentage of negative energy. Using a similar analysis, Asmussen and Bonde-Peterson (1974a), reported percentage gains in positive energy of 22.9% for the counter movement jump and 13.2%, 10.5% and 3.3% for the drop jumps from 0.233 m, 0.404 m and 0.690 m. No statistical data were published to substantiate these findings, but the poor performance in the squat jump was ascribed to energy wasted due to internal shortening in the early stages of contraction. The authors cited data from single muscle fibre experiments by Hill (1970) and Buchthal and Schmalbruch (1970) as evidence of "good opportunities" for the storing of energy in stiff muscle fibres. Komi and Bosco (1978a) adopted the same methods when they found that females were able to re-utilise 90% of their stored energy, whereas males, who jumped higher, only recovered 50%. These findings add considerable doubt to the reliability of the point mass form of energy analysis.

Alishensky (1986) showed that accounting for varying energy sources in a mechanical analysis of human motion was far from a simple task. He outlined what he termed a 'sources' and 'fractions' approach to modelling energy expenditure in human movement and clarified many of the confusing issues which had permeated the literature in the 1970's and early 1980's. He described three possible approaches for dealing with energy expenditure - joint power, segmental energy and total energy (based on positive work only). He questioned the latter
method in particular. He then clarified a number of the issues and formulated his ideas over a
series of inter-related papers in 1986. Considering the numerous problems highlighted by
Alishensky (1986) and the lack of information concerning the apportionment of energy between
and within segments, as outlined by Williams and Cavanagh (1983), it was decided that the joint
power approach should be adopted within this study. This would also build upon the work of
Elftman (1939), Bresler and Frankel (1950), Quanbury et al. (1975), Cappozzo et al. (1976), and
Winter and Robertson (1978). In addition, a number of modelling studies have been undertaken
in which the muscle moment power approach has been adopted for the determination of the
energy contributions made during jumping and landing (eg. Bobbert et al. 1987a, b; Sanders and
Allen 1993; McNitt, 1993).

The key problem in the study of segmental energy transfers remains that the human body,
although mathematically simplified to a linked kinematic chain, contains internal energy
sources, elastic components and multiple links at joints. As such, trying to determine the
exchanges and energetic costs of motion of one segment relative to another is virtually
impossible. Bobbert et al. (1985) took a different approach. They concentrated on individual
muscle energetics. That is they modelled the muscles of the lower limbs and determined the
motion and forces within the modelled muscles throughout the jumping action. In so doing they
were able to determine the energy exchanges at the muscle level. This also introduced muscle
models into the study of human jumping and provided a foundation to a series of forward
dynamics modelling studies which have added considerably to the understanding of jumping
mechanics.

**Forward Dynamics Modelling**

There are a number of different ways in which the mechanics of any system can be modelled.
Currently the most popular are the Newton-Euler, Lagrangian, and Kane's methods. Direct or
forward dynamics modelling requires the formulation of a series of equations to represent the
system. Then given the initial conditions of the system, including the inertia characteristics of
the body segments, and information on the joint moments, the motion of the rigid bodies which
make up the system can be computed. This process requires the solution of systems of ordinary
differential equations and so is numerically demanding. The complexity of these models vary
with the one by Hatze (1981) being perhaps the most complex used to date for the analysis of
jumping. Bobbert et al. (1986) and Pandy et al. (1990) used a simpler version of a muscle
model with the force-velocity characteristics being based on Hill's (1938) equation. In each case
there is a requirement for control. A simulation model requires a "central nervous system" to
control the sequencing and intensity of muscle activation within the individual muscle model.
Optimal control or dynamic optimisation is used to achieve this goal. A criterion is required for
the optimisation process to seek. One reason why the modelling of vertical jumping has been so
popular is that the criterion of maximum jump height is a very clear objective function. The moments at the joints within the simulation model are generated by Hill (1938) type muscle models representing selected muscles. The optimisation process thus becomes one of varying the muscle activation patterns until the segment motions produce the highest take-off velocity of the mass centre of the system. To date these types of simulation models have not been applied to the analysis of human walking because the objective function cannot be formulated so readily. Film, EMG and force plate data records of vertical jumps have been obtained to evaluate each model by comparing the model predicted output with the recorded movements of a series of subjects. The overall performance of direct dynamics models of vertical jumping has been said to be acceptable since they predict optimal vertical jump heights of around 0.45 m (eg. Pandy and Zajac, 1991; Bobbert and Soest, 1994).

Models which have been created in an endeavour to gain insight into jumping range from the simple model of leg extension (Alexander, 1989) to the earlier and more complex muscle driven direct dynamics model of Hatze (1981). Alexander's simple models do not have optimal control but simply switch the single muscle on maximally throughout the jump action. However, Alexander (1992a) advocated simplicity in modelling by stating

*Simple models are particularly useful in identifying basic principles because the simpler the model, the easier it is to discover which of its features gives rise to the observed effect. Alexander (1992a).*

Several examples of Alexander's work demonstrate the attraction of simplicity. The model of running long and high jump takeoffs, Alexander (1990), was an excellent example of the way in which a simple simulation model provided a powerful insight into the general mechanism of human jumping. It used two equal length massless limbs and a single muscle at the knee which was based on an angular variant of Hill's (1938) equation by Woledge, Curtin and Homsher (1985). The output from the simulation model clearly showed that there were different optimum velocities of approach and plant angles for human high jumping and long jumping. Because of its simplicity and lack of customised data, the model could not be used to optimise these variables for individual athletes. However, the resulting understanding of the basic underlying mechanisms were demonstrated with an elegance which has set a precedent in modelling studies. A second simple model, Alexander (1991), this time with two joints, focussed on three artificial but representative human throwing actions (put, underarm throw and overarm throw). It highlighted the influence of the timing of muscular actions to optimise terminal velocity of the projectile rather than of the total work being done. Alexander (1991) also responded to Ingen Schenau's (1989) "target" article on the apparent importance of proximal to distal sequencing of the lower limb joints in jumping. He was able to test Ingen Schenau's assumptions and to support a suggestion put forward by Bobbert et al. (1986) that proximal to distal sequencing was beneficial in jumping. The interesting challenge was that sequencing per se was not necessarily
the answer to maximum performance in jumping unless the final joint in the sequence was "driven by elastic recoil of a tendon".

Bobbert, Huijing and Ingen Schenau (1986) used a combination of muscle and inverse dynamics modelling in the study of vertical jumping. The muscle model that they developed was based on a series of six simplifying assumptions including for example that all fibres could be treated as similar and that fibre angle could be neglected. The force-velocity characteristics of the contractile component of the muscle model were based on Hill's (1938) equation. Series elasticity was included, although compliance within the series elastic components of the muscle was regarded as negligible in relation to the compliance of the tendon. The muscle model was used to investigate the human triceps surae muscle-tendon complex applied to jumping and was later incorporated into a forward dynamics model in which seven muscles of the lower limb could be simulated. This latter model became the central feature of a series of studies including one examining coordination in vertical jumping (e.g. Bobbert and Ingen Schenau, 1988). This particular paper tackled the problem of understanding the coordination necessary to optimise jumping performance and so joined the ongoing debate concerning the sequencing of muscle activation. Energy was considered, but a point mass approach only was used to obtain maximum values of energy produced. They reported graphs of the mass centre vertical acceleration against time, generated using Butterworth filtering and direct difference procedures, and the directly measured vertical ground reaction force time data. The curves were similar in shape but no statistics were reported to give an indication of the closeness of the match.

The simulation models of Pandy et al. (1990), Bobbert and Ingen Schenau (1988) and Bobbert and Van Soest (1994) have been used extensively in the study of vertical jumping. Graaf, Bobbert, Tetteroo, and Ingen Schenau (1987) used the muscle model of Bobbert et al. (1986) to examine the power output at the ankle for single leg takeoff jumps using a counter movement technique and an extended knee jumping technique. Although the peak ankle moments under both conditions were almost the same, the power produced in the extended knee counter movement jump was only 60% of that produced when the knee was allowed to flex. They were investigating the concept of power transfer from the knee to the ankle but concluded that other factors besides the transportation of power were contributing and referred in particular to the "catapult like" action which occurs when the force on tendonous structures decreases.

Fujii and Moriwaki (1992) developed a different four segment planar human jumping model, which had nine muscle groups based on the muscle model equations of Hatze (1977). The model was used to carry out a functional evaluation of two-joint muscles in squat jump motions. They concluded that two joint muscles were responsible for delivering power in a proximal to distal direction during jump takeoffs and that the power was transferred back through the joints. They also suggested that the two joint muscles controlled the angular velocities of the hip and
knee joints enabling the mono-articular muscles to generate enhanced power.

Modelling muscle is one of the central features of each of the forward dynamics models. Hill's (1938) equation of muscle has routinely been used but the excitation dynamics have varied. Commonly "bang-bang" control is employed. That is muscle is either maximally activated or is switched off. This is useful and justifiable when maximal effort actions are of interest and has been used effectively in modelling the push off phase of vertical jumping (e.g. Soest et al. 1993). Anderson and Pandy (1993) used a newer and more complex forward dynamics model of jumping (Pandy et al. 1992) to examine the storage and utilization of elastic energy during jumping. The addition of non "bang-bang" control of the muscle activation dynamics was added to the earlier model of Pandy et al. (1990). This enabled a better analysis of the downward phase of the counter movement jump to be achieved. They repeated a traditional study by comparing the performance of counter movement and squat jumping actions. The model had been evaluated using a variety of measures including jump height, joint kinematics and muscle activation patterns based on EMG recordings. They reported no differences in the amount of energy delivered to the skeleton in the counter movement jump and squat jump. They also showed that nearly the same amount of elastic energy had been stored in both jumps but that more elastic energy had been lost as heat in the counter movement jump. Also energy was stored in slightly different ways in the two jumps - in the counter movement jump, energy was stored resisting downward motion of the skeleton (drop in potential energy) whereas for the squat jump there was more work being done internally stretching the tendons and elastic tissues associated with the muscles. Jump height remained the same in both actions. Their finding was that elastic energy influenced efficiency more than jump height. Clearly the assumptions within any model influence the findings, but the model has been used extensively to examine jumping and has consistently been evaluated favourably in comparison with experimentation.

Power and coordination have been major topics of interest for the researchers using forward dynamics models of jumping. The role of bi-articular muscles in vertical jumping has been at the centre of this debate with Zajac's group in America disagreeing with Ingen Schenau's group in Amsterdam. Both research groups (Ingen Schenau's and Zajac's) support the concept of proximal to distal sequencing of muscle activation in jumping. However, the two groups do not agree about the role of bi-articular muscles. One group, represented by their most recent paper (Jacobs, Bobbert and Ingen Schenau, 1996) supports the idea that power is transferred via the gastrocnemius from the knee to the ankle by virtue of its bi-articularity. Bobbert, Hoek, Ingen Schenau, Sargent and Schreurs (1987) presented a physical model called "Jumping Jack" to demonstrate the consequences of altering the attachment and hence length of the gastrocnemius muscle and its effect on jumping performance. The basic argument put forward by Bobbert et al. (1987) is that at or near to the end of the range of motion in plantar flexion, the power output at the ankle is too large and at too high an angular velocity to be produced by muscular
contraction of mono-articular muscles and that power is transferred from the knee extensors via the gastrocnemius. Pandy and Zajac (1991) agree that the gastrocnemius is important in jumping, stating a 25% increase in jump height as a consequence of the action of the gastrocnemius, but dispute the bi-articularity argument. They replaced the gastrocnemius with a mono-articular ankle plantar flexor without decreasing the over jumping height achieved by their model. In this one topic is an illustration of both the strengths and the weaknesses of modelling. The strengths are contained within the flexibility and control offered to researchers. The ability to be able to change a single parameter, without altering others, enables idealised experimental studies to be conducted. However, if the model is not a true representation of the real world events then the model produces outputs and hence insights which are of limited value. The net validity of both models of jumping have been shown through comparisons with vertical jump heights predicted by the models and achieved by human subjects. However, there are enormous ranges of human vertical jumping performances. If the World record for vertical jumping of over one metre were to be used as the criterion, none of the models could match it. A poor jumper might achieve 0.20 m in jump height, whereas the models commonly produce an optimum vertical jump of about 0.45 m. These debates will continue, as will improvements in the models including the muscle models that they contain. However, as each group refines its models and rethinks the implications of the findings, it is interesting to note that their ideas are coming closer together.

Conflicting theories about the contributions made by bi-articular muscles to power production and transfer in the lower limbs in vertical jumping has been at the centre of a debate since the early 1980's. Prilutsky and Zatsiorsky (1994) presented an elegant summary of this debate and also demonstrated a way of clarifying some of the inconsistencies. Ingen Schenau et al. (1985, 1990), and Bobbert and Ingen Schenau (1988) showed that during vertical jumps energy was transferred from proximal to distal joints by the unique action of bi-articular muscles. The opposite view, that power was transferred from distal to proximal segments was held by Pandy et al. (1990) and Pandy and Zajac (1991). Prilutsky and Zatsiorsky (1994) believed that the essence of the disagreement was in the definition of 'transfer of mechanical energy'. They used inverse dynamics to determine the moments about ankle, knee and hip joints in jumping and then applied a model of the musculo-skeletal system to quantify the contributions made by each of eight muscles to the joint muscle moments. Thus by calculating the forces and velocities of the individual muscles they were able to track the exchange of energy between segments of the body. Three activities were studied including squat vertical jumping, drop landing and running. The results obtained for power production by the muscles were compared with muscle moment power values and shown to be in very close agreement for landing and running. The level of agreement in squat jumping was not quite as good, but this discrepancy was attributed to the fact that the joint angle ranges measured for the squat jump task were outside the range of joint angles used in the original Russian study from which the model had been developed.
2:4 SUMMARY

From its introduction as a measuring instrument, the force plate has been a key element in biomechanics research. Despite its widespread usage, there have been relatively few papers on calibration of force plates and processing of force plate data. Early studies of jumping used the force plate either as a timing instrument or for point mass analyses using the integration of vertical force time traces. Synchronised visual image and force plate data, and in some cases EMG data, have been used in inverse dynamic, quasi-static and segmental energy analyses of human motion and as an evaluative data source for forward dynamics models of vertical jumping and landing. Irrespective of the methods used, whenever differences in findings for studies of similar activities have been reported, consideration of the protocols used has revealed underlying discrepancies. Modelling has proved to be a powerful tool adding to experimental studies, but differences in modelling definitions, components and interpretations have lead to additional conflicts. The following three chapters investigate some of the experimental discrepancies in the studies of human jumping whilst the final chapter coordinates the ideas from previous experimental and modelling studies in an evaluation of the new data.
CHAPTER 3

DROP JUMPING: FORCE-TIME MEASUREMENT AND INTEGRATION

3:1 INTRODUCTION

Cavagna et al. (1971), Asmussen and Bonde-Peterson (1974a, b) and Bosco and Komi (1978a, b) studied the effects of the stretch-shortening cycle on the performance of the leg extensor muscles during human vertical jumping. In this chapter, similar jumping actions have been used to re-examine these effects, and in particular to examine the methodology employed. A series of questions about the measurement processes used previously have been raised. Asmussen and Bonde-Peterson (1974a, b) and Bosco and Komi (1978a, b) used a force plate as a sophisticated "timing mat" and made limited use of the force-time recordings. They both also used analog chart recording techniques to capture the force data. Cavagna et al. (1971) reported different findings to those obtained by the other two research groups. One aspect of this chapter was to extend the use of the available force data by increasing the measurement precision offered by digital rather than analog force recording techniques. A series of experiments was designed to check the results obtained by the three research groups and to discover whether improvements in the measurement procedures would influence the findings and conclusions.

The current chapter, has been divided into two main sections. Section 3:2 examines the variation in takeoff velocity as determined from time in flight and from the impulse generated during the jump. Section 3:3 concentrates on drop jumping and in particular upon the influence of drop height on subsequent vertical jump performance. Within each of these sections the measurement and resulting calculation processes have been examined.

Bosco and Komi (1978a, b) used the terms, "static jump" (SJ), "counter-movement jump" (CMJ) and "drop jump" (DJ) to describe three variations on a basic jumping action. The purpose of this experiment was to answer the following specific questions:

(i) was it possible to use flight time as an accurate indicator of takeoff velocity for vertical jumping?

(ii) when performing a drop jump, what was the relationship between the platform height and the actual distance dropped?

(iii) when performing a counter movement jump or drop jump, what was the influence of pre-stretching the muscle tendon units as a result of a counter movement or drop landing on the height of the subsequent jump?
(iv) what were the implications of the answers to these questions on the findings reported in earlier studies of jumping?

Question (i) has been answered using a direct comparison of the takeoff velocity values calculated from free flight times and force-time integrals of vertical ground reaction force traces for counter movement and squat jumps. Question (ii) has been answered using comparisons of landing impulse values determined directly from nominal drop height and indirectly from total ground contact impulse. Question (iii) has been answered by comparing jump heights achieved following drop jumps with those achieved following counter movements or squats, and by grouping drop jump heights into Low, Medium and High drop categories based on the data obtained in response to question (ii). A combination of graphical and statistical techniques have been used to answer these questions. Question (iv) has been the focus of the discussion section for this chapter.

3:2 FLIGHT TIME AND IMPULSE - An examination of calculation procedures

In a study by Challis and Kerwin (1985), the calculation of takeoff velocity from free-flight time had been shown to be un-acceptable if time had been determined directly from the hard copy output of a transient chart recorder, (Bryans Transcribe 10). A Pearson product moment correlation of takeoff velocity calculated from free flight time and takeoff velocity calculated from the force-time integral of 0.757 (n = 52 trials) was obtained. This indicated that less than 60% of the variability in calculated velocity at takeoff could be accounted for by the variability in flight time estimated from the chart recorder output. However, when the takeoff velocities were calculated using flight time data obtained from digitised recordings of the force traces, using analog to digital conversion sampling at 500Hz, the correlation coefficient increased to 0.955. A question was therefore raised about the validity of the data obtained by Asmussen and Bonde-Peterson (1974a, b) and Bosco and Komi (1978a, b), since both studies relied upon time data obtained from chart recordings.

3:2.1 METHOD

Subjects

All the subjects were physically active. They were tested in two groups. Group A was used to investigate free-flight times as a predictor of takeoff velocity in static and counter-movement jumps. Group B, a sub-set of group A, Table 3.1, was used in the examination of the drop jump ground reaction impulse. By dropping from increasing heights, the effect of stretching the tissues of the legs, primarily the extensor muscle-tendon units, will have increased. This
"stretching load" will have risen from the counter-movement jump through the drop jumps until it reached a maximum at the greatest drop height.

Table 3.1. Mass, Height and Age data for subjects in squat, counter movement and drop jump tests.

<table>
<thead>
<tr>
<th>Variable</th>
<th>GROUP A</th>
<th></th>
<th>GROUP B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males (n=10)</td>
<td>Females (n=12)</td>
<td>Males (n=6)</td>
<td>Females (n=8)</td>
</tr>
<tr>
<td>MASS (kg)</td>
<td>73.87 (±7.83)</td>
<td>59.99 (±9.38)</td>
<td>73.02 (±8.48)</td>
<td>56.35 (±5.58)</td>
</tr>
<tr>
<td>HEIGHT (m)</td>
<td>1.76 (±0.08)</td>
<td>1.65 (±0.08)</td>
<td>1.72 (±0.06)</td>
<td>1.63 (±0.05)</td>
</tr>
<tr>
<td>AGE (yr)</td>
<td>28.80 (±8.90)</td>
<td>26.00 (±6.30)</td>
<td>27.33 (±4.70)</td>
<td>24.00 (±4.90)</td>
</tr>
</tbody>
</table>

The three jumps investigated were similar to those specified by Komi and Bosco (1978a):

Static Jump, (SJ) - a jump for maximum vertical height instigated from a stationary squat position, with no counter movement permitted.

Counter-Movement Jump, (CMJ) - a jump for maximum vertical height preceded by a vigorous squatting counter movement.

Drop Jump, (DJ) - a jump for maximum vertical height preceded by a drop from a variable height platform. For these jumps the subjects dropped from heights of 0.15m, 0.30m, 0.45m, 0.60m, 0.75m and 0.90m. (These drop jumps are labelled DJ15 to DJ90).

**Equipment**

A force plate, (Kistler 9281B12), was used to collect a vertical force-time record of each jump. Data were sampled at 500 Hz via a 12 bit analog to digital converter (ADC) within a Laboratory Interface (Cambridge Electronic Design 502) to a minicomputer (PDP11/23+). For each type of jump the total impulse was calculated using the Trapezium Rule method of numerical integration with the time slice width of 0.002 s. The same time resolution was used to calculate the free flight-time for the subsequent vertical jump.

**Procedure**

Following a warm up and familiarisation period, subjects performed a series of squat and counter-movement jumps. For all the trials the subjects adopted a symmetrical position with
hands on hips throughout the jump and landing (akimbo position). In the case of the static jumps, a goniometer was used to measure knee angle in the squat position. This served two purposes; it ensured a measure of inter-trial knee flexion angle consistency and provided a true static period which reduced the influence of benefit gained from the muscle stretch-shortening cycle. In each case, the subjects were asked to attempt to attain maximum jump height. Providing that the subject began from the required position and returned to a controlled, stable standing position and that the foot contact was wholly within the force plate surface area, the trial was regarded as successful. Three trials of each type of jump were obtained in a randomised order. The data were stored on computer discs for later analysis. For the squat jump trials, if there was any obvious counter-movement observed on the force trace (initial negative impulse generation), the trial was not used in the analyses.

**Flight time**

Flight time was defined as the interval between takeoff, the first zero vertical force reading, and landing, the first non-zero force reading, see Figure 3.1a. Noise in the ADC unit resulted in readings of $\pm \frac{1}{2}$ least significant bit (LSB) in a 12-bit range. There were thus no true zero values. Data were stored internally in unsigned 16-bit binary format and so an ADC count of $\pm 164$ was equivalent to $\pm \frac{1}{2}$ bit. A threshold level on the vertical force channel ($F_z$) was set in the software at the $\frac{1}{2}$ bit level (equivalent to 25N). Once time of flight had been established, an assumption was made that the subject's body position and hence relative mass centre height was the same at takeoff and landing. The free flight motion (Figure 3.1b) was thus treated as symmetrical and therefore the time to reach the top of the jump ($t_{up}$) was half the total flight time. Using equation 3.1, one of the equations of uniformly accelerated motion, the takeoff velocity based on time of flight ($v_{time}$) was estimated.

\[
\begin{align*}
\text{v}_{\text{top}} &= \text{v}_{\text{time}} - g \cdot t_{\text{up}} \\
[ v &= u + at ]
\end{align*}
\]

where $\text{v}_{\text{top}}$ = velocity at the top of the jump ($=0$), $a$ = acceleration ($-g$) and $t = t_{up}$. Thus the velocity at takeoff determined from flight time ($v_{time}$) could be calculated.

Errors arising from incorrect detection of takeoff and landing were not likely to exceed one time interval (0.002 s). Errors associated with the assumption that the flight of the subject's mass centre was symmetrical were less predictable. By also calculating the takeoff velocity from the force time impulse during the takeoff action it was possible to check whether symmetry was maintained by the subjects.
Figure 3.1a. Determination of flight time from digitised Force data.
Four key data points marked as circled black dots. Takeoff occurs between dots 1 and 2 and Landing between dots 3 and 4. The mid point between each pair of dots would be the best estimate for the start and end of the period of flight, i.e. the time interval between dots 1 & 2 and between dots 3 & 4. This is the same time as the time interval between dots 2 and 4. Thus flight was defined as the time interval between the first below and first above the ½LSB threshold (shown as the dashed line).

Figure 3.1b. Counter-Movement Jump (Vertical Force-time trace).
Full vertical force-time trace of a sample CMJ beginning prior to the start of the downward motion (start) and including takeoff, landing and return to stationary standing. Note that the data in Figure 3.1a corresponds to the flight time interval.
**Takeoff Impulse**

Takeoff impulse was determined by integration of the force time trace between the start of the movement and takeoff for the jump (Fig. 3.1b Start and Takeoff). Numerical integration using the Trapezium rule was applied. Data had been recorded at 500 Hz and so discrete data points at 0.002 s intervals were available. With the assumption that there was no air resistance, equation 3.2 was applied, to determine the change in velocity of the subject's mass centre from its initial and assumed zero velocity position at the "Start".

\[
v_{\text{imp}} = \frac{1}{m} \sum_{\text{Start}}^{\text{Takeoff}} (F_z - mg) \, dt
\]

Where, \( v \) = velocity (m \cdot s\(^{-1}\)), \( m \) = subject mass (kg), \( F_z \) = ground reaction force recorded at the force plate surface (N), \( g \) = gravitational acceleration (m \cdot s\(^{-2}\)), and \( dt \) = the time interval between each successive force reading (s).

Using a process of successive summation, the "area so far function" and hence velocity at takeoff (\( v_{\text{imp}} \)) was calculated. The net force was used, that is the force value relative to the subject's weight, and numerically integrated from the "Start" to "Takeoff" as shown in Figure 3.2. The resulting impulse values were scaled by \( 1/m \) to obtain velocity data. This process was repeated for a total of twenty subjects (group A Table 3.1) performing two successful jumps. A total of 43 jump trails were analysed.

### 3.2.2 RESULTS

**Flight Time**

To examine the validity of using flight time to calculate take-off velocity, \( v_{\text{time}} \) was compared with \( v_{\text{imp}} \) using a "t" test and Pearson Product Moment correlation coefficient (\( r \)). The summary of these analyses are presented in Table 3.2, with the full data presented in Appendix (3.1).

<table>
<thead>
<tr>
<th></th>
<th>( n=43 )</th>
<th>( v_{\text{imp}} )</th>
<th>( v_{\text{time}} )</th>
<th>( v_{\text{time} + \delta t} )</th>
<th>( v_{\text{time} - \delta t} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.226</td>
<td>2.230</td>
<td>2.239</td>
<td>2.220</td>
<td></td>
</tr>
<tr>
<td>St.Dev</td>
<td>±0.304</td>
<td>±0.266</td>
<td>±0.266</td>
<td>±0.266</td>
<td></td>
</tr>
<tr>
<td>'t'</td>
<td>0.039</td>
<td>0.134</td>
<td>-0.057</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>0.943</td>
<td>0.943</td>
<td>0.943</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

'\( t \)' = t test data, \( r \) = Pearson Product Moment Correlation Coefficient, velocity data (m \cdot s\(^{-1}\)).

\( \pm \delta t \) = effect on the velocity of takeoff caused by adding or subtracting 0.001 s to the estimated flight time.
Figure 3.2. Force-Time Integral for the counter-movement jump.

Figure 3.3. 't' score data of $v_{imp}$ and $v_{time}$ with time offsets $\pm \delta t$ s.
From the mean and standard deviation scores it would appear that the magnitude and distribution of velocity values obtained by both methods were very similar. The value of 't' is small at less than 0.04 and clearly shows that the average values obtained by both methods can be considered the same. However, the correlation coefficient 'r' indicates that the match between the two data sets was not perfect. For the current purposes, having a significant correlation coefficient is not helpful unless the value of r is also high. With r=0.943, approximately 90% of the variability in the velocity data determined from impulse data was accounted for using the flight time. The error associated with mis-timing the flight based on 0.002 s time intervals is small. Since the takeoff velocity calculation was based on half the flight time, each of these time offsets would be 0.001 s. In Table 3.2 the two columns on the right, $v_{\text{time}+\delta t}$ and $v_{\text{time}-\delta t}$, show the effect of adding and subtracting half a standard time interval and recalculating the velocity values and the 't' scores. With the same values being added or subtracted, the mean score is adjusted without altering the standard deviation. The correlation coefficient will also be unaltered as the shape of the new data set remains constant. The 't' score however will change as the difference between the modified and the original impulse data set changes. By adding or subtracting the effects of 0.001 s to the flight time based velocity data, the difference between these data and the impulse data increased in both cases. The smallest difference remained the original value and supported the original estimation procedure for determining flight time. Figure 3.3 contains a graph showing the effects of adding and subtracting one time interval (±0.002 s) to the original flight time data, followed by re-calculation of the takeoff velocity and comparison with the criterion impulse data using a 't' test. The linear relationship between flight time and takeoff velocity (equation 3.1) results in a linear fit with a zero 't' score at -0.0004 s. When the mean takeoff velocity $v_{\text{imp}} \pm 2$ SD was used to predict height jumped and compared with the values obtained using these velocities and the re-calculated values based on modified flight times (ie. with the -0.0004 s difference), the resulting range in the difference in height jumped was 0.6 mm to 1.1 mm. When compared to the possible lack of symmetry in the position of the subject's mass centre at takeoff and landing this ~1 mm error was deemed to be negligible.

A linear regression analysis on the two sets of height jumped data was used to determine the level of confidence which could be placed on values of takeoff velocity obtained using flight time as opposed to impulse (Table 3.3). In Figures 3.4a, and 3.4b confidence intervals at the 95% levels have been shown. Overall the confidence with which jump height was predicted from flight time was very high. Effectively 95% of all values obtained were within ±0.005 m of the value obtained using takeoff impulse. However, when single values only were used the confidence interval dropped to ±0.044 m if all the data were included and to ±0.033 m when the "rogue" outliers were removed (Table 3.4). It was reasonable to expect therefore that in 95% of all trials the predicted height jumped by the subject was not likely to vary by more than about 3 cm from the actual height attained.
Figure 3.4a. Regression analysis, Jump Height from Flight time.

The outliers in graph 3.4a were regarded as unusual data points as they lay well outside the 95% confidence interval. By removing these two values the confidence intervals were reduced as shown in Table 3.4. These revised data have been plotted in figure 3.4b.

Figure 3.4b. Regression Analysis, Jump height from Flight time with 'outliers' removed.

The inner banding represents the the confidence interval when predicting from the regression equation and the outer banding the confidence interval when using individual values as input. The latter will be the case in normal circumstances when flight times for individual jump trials are being used to estimate height jumped.
Table 3.3. Linear Regression Prediction of Jump Height (m) based on mean Flight Time (0.227 s) input.

<table>
<thead>
<tr>
<th></th>
<th>Lower</th>
<th>Forecast</th>
<th>Upper</th>
<th>95% CL Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=43</td>
<td>Mean</td>
<td>0.250</td>
<td>0.257</td>
<td>0.264</td>
</tr>
<tr>
<td></td>
<td>Point</td>
<td>0.213</td>
<td>0.257</td>
<td>0.301</td>
</tr>
</tbody>
</table>

Table 3.4. Linear Regression Prediction of Jump Height (m) based on mean Flight Time (0.227 s) input.

<table>
<thead>
<tr>
<th></th>
<th>Lower</th>
<th>Forecast</th>
<th>Upper</th>
<th>95% CL Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=41</td>
<td>Mean</td>
<td>0.249</td>
<td>0.254</td>
<td>0.259</td>
</tr>
<tr>
<td></td>
<td>Point</td>
<td>0.221</td>
<td>0.254</td>
<td>0.287</td>
</tr>
</tbody>
</table>

Takeoff Impulse

All the previous analyses were based on the assumption that the jump heights generated from impulse data were the criterion set. However, the process of data capture and quantisation to digital format inevitably introduced error. The force plate and amplifier system was checked to be within the manufacturer's accuracy range at <1% for vertical force F₂. The ADC (CED502) was checked to be within the specified range of ±½LSB. Systematic error arising from poor calibration and scaling factor errors was therefore not a concern. Also random error due to noise in the measurement systems could be regarded as low in amplitude and with the large number of readings per trial recorded (1024), it was assumed that the mean error was zero. Integration introduced two forms of error, constant and approximation. Constant error arising from the process of integration was assumed to be small and has not been included in this study. However, its effects have been examined in more detail as part of the rebound jumping study reported in Chapter 5.

Approximation error would increase as the width of the time slices used in the area estimates increased. Samples recorded at 500 Hz should produce a better estimate of a complex curve and hence area than samples recorded at 100 Hz. To check the effects of varying the sampling frequency on area estimation, vertical jump data were recorded at 2.5 kHz and then areas were calculated with decreasing frequencies, 1.25 kHz, 500 Hz, 625 Hz, 250 Hz, 125 Hz, 100 Hz, 50 Hz and 25 Hz and compared with the area obtained using the original 2.5 kHz data set. The difference between the calculated area in each case was expressed as a percentage of the area at 2.5 kHz. The average of six trials for two subjects have been plotted in Figure 3.5 with the accompanying data listed in Table 3.5.
Table 3.5. Mean Impulse generated takeoff velocity at reducing sampling frequencies (n=6 trials).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Subject 1 (m·s⁻¹)</th>
<th>Subject 2 (m·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>2.262</td>
<td>2.814</td>
</tr>
<tr>
<td>1250</td>
<td>2.258</td>
<td>2.810</td>
</tr>
<tr>
<td>625</td>
<td>2.249</td>
<td>2.806</td>
</tr>
<tr>
<td>500</td>
<td>2.248</td>
<td>2.806</td>
</tr>
<tr>
<td>250</td>
<td>2.232</td>
<td>2.792</td>
</tr>
<tr>
<td>125</td>
<td>2.184</td>
<td>2.791</td>
</tr>
<tr>
<td>100</td>
<td>2.166</td>
<td>2.727</td>
</tr>
<tr>
<td>50</td>
<td>2.100</td>
<td>2.628</td>
</tr>
</tbody>
</table>

Figure 3.5. Integration percentage error difference in area plotted against sampling frequency.

The added advantages in area estimation obtained when using high sampling frequencies were balanced against the disadvantages of increased data volume. A rate of 500 Hz for all the jump data was selected. This retained the desired accuracy of <1%.

3.2.3 DISCUSSION

The first question raised at the beginning of this chapter concerned the relationship between flight time and the vertical force-time integral when trying to calculate takeoff velocity in vertical jumping. In particular, the purpose was to ascertain the confidence with which takeoff velocity could be determined. It is recognised that certain assumptions concerning flight symmetry have been made, but use of digital data sampled at 500 Hz was shown to produce estimates of takeoff velocities which were close to the values calculated from the vertical force time integral determined using the Trapezium Rule. The correlation coefficient of 0.943 was in close agreement with the value reported in a previous study of 0.955 (Challis and Kerwin, 1985). In both cases approximately 90% of the variability in jump height obtained from the force time integral was accounted for by the variability in flight time.

Linear regression analysis was conducted on a total of 43 jump trials with the exclusion of two outlier points. It was shown that if the regression equation was known, predictions in jump heights would be within ±0.005 m of the values obtained using the force-time integral. When an individual flight time was used as input to the same regression model, the width of the
confidence interval with which jump height could be predicted increased to approximately ±0.03 m. The latter case is the one of particular interest and relevance to the current chapter.

Throughout the first part of the study, the data obtained by integration had been regarded as the criterion against which other values had been compared. It was therefore important to establish that the errors associated with approximating the force-time curve as a series of thin slices for the purposes of numerical integration were small. With the sampling frequency set at 500 Hz, the errors in estimating area were found to be less than 1%. This converted to an error in jump height of ±0.003 m, or approximately 10% of the error encountered when using flight time.

In the following section of the study, the flight phase between rebounding from a drop and landing was again used to estimate takeoff velocity and hence takeoff impulse. The effect of the errors highlighted in the current section have been used to limit the calculations in the following drop jumping section.
3:3 DROP JUMPING

The apparent simplicity of the calculation procedures connected with the use of drop jumping as a means of studying the stretch-shortening cycle made it very attractive. Asmussen and Bonde-Peterson (1974a, b) had used an integral of the force-time history for confirmation of take-off velocity, but they like Komi and Bosco (1978a, b), based the remainder of their experimental calculations upon free-flight time. In addition, parameters obtained for trials in which a drop was employed prior to a rebound jump were based upon a nominal specification of the height of drop from a series of raised platforms. Observation of subjects performing drop jumps in the laboratory indicated that some compensatory strategies were employed by subjects as the height of the platform increased. In the event that a subject squatted down slightly and hence lowered the mass centre prior to free-fall from a raised platform, the total area under the force time curve for a drop jump would either over-estimate the take-off velocity or under-estimate the subject’s body weight. Since the take-off velocity and hence takeoff impulse was determined independently from the following free-flight phase, the impulse calculated from the subject’s weight during ground contact would be less than that required to maintain the body in a stationary and supported position. It would therefore appear that the previously reported research had not taken into account this anomaly. The findings from the previously published data were therefore in question.

From section 3:2 of this chapter it has been shown that predicting jump height from the free flight time was possible, providing that the confidence intervals reported in Table 3.4 were acknowledged. The next part of the analysis used this information to facilitate the analysis of the drop and rebound phases of the remaining jumps.

3:3.1 METHOD

Subjects

The details of the subjects for this part of the study were included in Table 3.1 under the subheading Group B. There were six males and eight females drawn from the earlier study. All those who took part in this demanding experiment were physically active and with a mean age of 27±4.7 years for the men and 24±4.9 years for the women.

Equipment

The same force plate and computerised data capture systems were used as those described in section 3:2.1, but in addition a series of six wooden platforms 1.2 m square by 0.15 m high were
constructed. The platforms were placed in a variable height stack close to the force plate so that the subjects could drop from the platform onto the force plate with the minimum forward movement of the body. The drop heights could be varied from 0.15 m to 0.90 m using the six platforms in combination.

Procedure

Following the previously described period of warm up, familiarisation and vertical jumping, the subjects practised dropping from platforms of varying height. Subjects were asked to drop from the raised platform, land two footed on the force plate and immediately rebound as high as possible before re-impacting the plate and coming to rest in an upright standing position. Trials were rejected if the subjects experienced any problems with balance or control. Subjects were free to opt out of the testing process at any height if they were unhappy. All members of group B were able to complete the test in full. The sequence was CMJ1, SJ1, DJ151 to DJ901. This sequence was then repeated beginning with DJ902 and ending with CMJ2. Figure 3.6 is a photographic sequence showing the 0.30 m platform configuration with a female subject dropping and rebounding from the force plate.

Although each subject positioned themselves close to the edge of the raised platform, practice was still required to facilitate a consistent drop. Once again the hands were positioned on the hips to replicate the previously reported studies. Each subject was free to make minor adjustments to the platform's overall position relative to the force plate. This was necessary to accommodate the varying sizes of the subjects. In each case the subjects were free to start the drop in their own time. The force data capture sequence was triggered manually during the time that the subject was in free fall from the raised platform. Data for each trial were only acceptable if the subject rebounded and landed within the surface area of the force plate. When the subject was fully familiar with the requirements of the test, they performed a series of drop jumps from heights of 0.15 m increasing in steps of 0.15 m up to a maximum of 0.90 m. The drop jumps were then performed in reverse order from 0.90 m down to 0.15 m. A total of 12 successful drop jumps were executed by each subject.
Figure 3.6. A photographic sequence showing a female subject performing a drop jump from a platform of nominal height 0.30 m, (DJ30).
**Ground contact rebound impulse**

During the rebound ground contact phase, the total impulse was considered to comprise three components; landing impulse (LI), support impulse (SI) and takeoff impulse (TI). Figure 3.7a shows the total vertical force-time trace for the drop, rebound, flight and landing with respect to the body weight. Figure 3.7b, highlights the rebound ground contact phase of the jump and shows the sub-divisions into LI, SI and TI. The results from section 3:2 enabled the total ground reaction impulse (GRI) to be apportioned into three sections; Takeoff Impulse (TI), Support Impulse (SI) and Landing Impulse (LI). The total Ground Reaction Impulse (GRI) was determined by numerical integration of the rebound phase of the force-time trace. Takeoff velocity, calculated from flight time, multiplied by body mass enabled the Takeoff Impulse to be determined. The same criteria for identifying the start and end of the flight phase as outlined in section 3:2 were used and the errors associated with predicting takeoff velocity were used to limit the range of estimates for the values of TI. Support impulse, (SI), was determined from subject weight and ground contact time. Landing impulse (LI) was then calculated as the difference between GRI and (SI + TI).

**Drop Height**

In previous studies (Asmussen and Bonde-Peterson 1974a, b, Bosco and Komi 1978a, b) the value for the drop height was defined as the height of the platform from which the subjects dropped. The height was used to calculate "stretch load" on the muscles by multiplying body weight by height dropped. In reality this was the nominal drop height (NDH) of the platform. However, the tendency of subjects to lower their mass centres by slightly bending the knees prior to "slipping off" the supporting platform was likely to reduce the free fall distances. To calculate the actual height dropped it was necessary to determine the impact velocity and then work backwards to determine the height from which a subject must have dropped to attain the required impact velocity. Using landing impulse and subject mass, the impact velocity and hence the “calculated drop height” (CDH) was determined. By ignoring air resistance and assuming constant gravitational acceleration the standard equation of motion with constant acceleration was modified to produce equation 3.3. This calculation was repeated for all trials. In addition the takeoff impulse values were modified to take account of the possible errors associated with flight time estimations of takeoff impulse. Jump height values were determined from takeoff velocities (using equation 3.1) and then comparisons were made between NDH and jump height and CDH and jump height.

\[ v^2 = u^2 + 2as \]

\[ \text{CDH} = \left( \frac{LI}{m} \right)^2 \cdot \frac{2g}{m} \]

where CDH = calculated drop height (m), LI = landing impulse (N . s), m = mass (kg) and g= gravitational acceleration (m . s\(^{-2}\))
In Figure 3.7a the trace begins before the first landing from the drop and ends when the subject returns to rest in a standing position. The section between Drop Landing and Takeoff has been expanded in Figure 3.7b to show the integration areas for determining the Calculated Drop Height rather than Nominal Drop Height.

In Figure 3.7b the Ground Reaction Impulse (GRI) has been divided into Landing Impulse (LI), Takeoff Impulse (TI) and Support Impulse (SI). Calculated Drop Height (CDH) was determined using the LI divided by mass to obtain landing velocity under free fall.
3.3.2 RESULTS

The full tables of data for the SJ, CMJ and all DJ conditions appear in Appendix 3.2. A summary of mean values for each group and for each type of jump have been included in Table 3.6.

Table 3.6. Summary of Mean Jump Heights (JH) and Mean Calculated Drop Heights (CDH) attained by Male (n=6) and Female (n=8) subjects executing three types of jump; SJ, CMJ and DJ from Nominal Drop Heights (NDH). All values in metres.

<table>
<thead>
<tr>
<th>Jump Type</th>
<th>Male JH</th>
<th>Male CDH</th>
<th>Female JH</th>
<th>Female CDH</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ</td>
<td>0.315</td>
<td>-0.2*</td>
<td>0.255</td>
<td>-0.2*</td>
</tr>
<tr>
<td>CMJ</td>
<td>0.395</td>
<td><em>0.0</em></td>
<td>0.286</td>
<td>*0.0</td>
</tr>
<tr>
<td>DJ15</td>
<td>0.333</td>
<td>0.147</td>
<td>0.286</td>
<td>0.148</td>
</tr>
<tr>
<td>DJ30</td>
<td>0.367</td>
<td>0.264</td>
<td>0.285</td>
<td>0.271</td>
</tr>
<tr>
<td>DJ45</td>
<td>0.355</td>
<td>0.380</td>
<td>0.292</td>
<td>0.398</td>
</tr>
<tr>
<td>DJ60</td>
<td>0.360</td>
<td>0.489</td>
<td>0.288</td>
<td>0.516</td>
</tr>
<tr>
<td>DJ75</td>
<td>0.356</td>
<td>0.625</td>
<td>0.283</td>
<td>0.630</td>
</tr>
<tr>
<td>DJ90</td>
<td>0.344</td>
<td>0.726</td>
<td>0.275</td>
<td>0.752</td>
</tr>
</tbody>
</table>

* = estimated height regarding CMJ as 0 m and SJ as -0.2 m

Drop Height

From Table 3.6 it can be seen that the height jumped from a counter movement jump was greater than that achieved in a squat jump. This was particularly marked for the male subjects, where the difference was 8 cm which represented a 25% increase in jump height compared with the SJ condition. The corresponding female data were considerably smaller at 3 cm and 11% respectively. In all cases the male subjects jumped higher than the female subjects. The mean male jump heights ranged from 0.333 m to 0.367 m (34 mm) compared with a corresponding range of 6 mm (0.286 m to 0.292 m) for the females. There was no clear best drop height for male subjects with similar jump heights resulting from drops between 0.26 m to 0.62 m. When a quadratic function was fitted to the mean data, the predicted best jump height for the male subjects was from a drop height of 0.54 m with the corresponding best drop height for the female subjects being 0.43 m. However, these data were based on the nominal dropping heights commonly reported by others (eg. Komi and Bosco 1978a). The equivalent "best drop heights" for the calculated drop height data were lower at 0.45 m for males and 0.37 m for females.

In all cases the mean jump heights attained from the drop jumps were higher than those from the squat jumps.
The mean results however, concealed individual subject differences, and so the performances by each subject were considered separately. Data from the tables in appendices 3.2a-3.2f were used to plot the graphs shown in figures 3.8a and 3.8b for the male and female data respectively. In addition each subject's data set was fitted with a quadratic function. The resulting summary shows that there was little pattern to the data with four males and two females only showing the previously reported optimum performance in the middle of the drop height range (Asmussen and Bonde-Peterson, 1974a; Komi and Bosco, 1978a). Two females, HB and LB, produced jump performances which decreased with increasing drop height whilst two others, JB and EF, achieved their best jump performances at the low and high ends of the range and the worst performance in the mid range. It would appear from the individual subject performances that there was no clear relationship between drop height and subsequent jump height. This was different to the observation by Asmussen and Bonde-Peterson (1974a) who found that the best jump height was attained from a 0.404 m drop height and that jump height performances from the three drop heights used were better than the jump heights attained following a counter movement. The current findings were also different to those published by Komi and Bosco (1978a) who found that dropping from heights between 0.45 m and 0.65 m produced better jump heights than counter movement jumps. Cavagna et al. (1971) had not found this, reporting no significant differences between counter movement and drop jump performances. Similarly, Bedi et al. (1987) did not find any significant differences between jump heights attained following a drop, although they did find that counter movement jumps always produced better jump heights than any drop jump for all subjects.

Linear regression analyses were undertaken with all the male subject data and all the female subject data treated separately. The resulting graphs are shown in figures 3.9a and 3.9b. The male data indicated that there was a slight drop in performance as drop height increased. The female data indicated the opposite. However, the net effect was very small and the indication overall was that there was no clear evidence of any trend. In Figure 3.10 both sets of data (6 male and 8 female subjects by 12 jumps each, N=164) have been plotted. Individual profiles were considered for comparison with previously published data. Although a quadratic function had been used to "fit" the data in figures 3.8a, 3.8b, there was no clear justification that this was appropriate or optimal. Also, the newly calculated drop heights were no longer in equal step sizes and so did not fall into neat categories, as would be the case for NDH, and therefore direct comparison with previously published data was inappropriate. A second fitting procedure was employed using a quintic spline adapted from Yeadon (1984), and based on Wood & Jennings (1979). This required estimates for the error at each point. A single unbiased estimate of the variance, Var(x), was obtained for each pair (x₁ and x₂) using the method proposed by Shchigolev (1965) pages 415-419, and shown in equation 3.4.

\[ \text{Var}(x) = \frac{1}{2} (x₁ - x₂)^2 \] 3.4
Figure 3.8a. Calculated Drop Height against Jump Height (Male data).

Figure 3.8b. Calculated Drop Height against Jump Height (Female data).
Figure 3.9a. Linear Regression (Male).

Figure 3.9b. Linear Regression (Female).
Figure 3.10. Linear Regression (Male and Female Data combined).
For each subject, twelve coordinate pairs, representing drop height and jump height, were utilised. From the resulting 6 standard deviation estimates a mean value was determined to constrain the fit throughout the data range. This had the advantage that the variance never approached zero but the limitation that it tended to under-estimate extreme differences. In addition, the whole calculation process was carried out on the traditional nominal drop height data for comparison with previous studies. By referring to the resulting splines it was possible to generate two sets of predicted jump heights from the calculated and nominal drop heights. These are shown in Figure 3.11.

From Figure 3.11 it can be seen that there was a peak in the mid range of the data. However, the range of jump heights was less than 0.005 m irrespective of the calculated height of the drop. This variability is smaller than the anticipated mean error range arising from the calculation of the rebound jump height and supports the previous observation that the height of the drop did not appear to result in an optimal jump response from any particular height of drop. In this analysis the height jumped appeared to remain at 0.3 m for calculated drop heights ranging from 0.1 m to 0.7 m.

When the male and female data were considered separately, the tendency of subjects to reduce the height from which a drop was made as the height of the platform increased was observed. Figure 3.12 shows the mean and standard error bars for males and females as nominal drop height increased from 0.15 m to 0.90 m. The corresponding calculated drop heights range from 0.147 m up to 0.752 m. In both groups it was noted that once the height of the platform increased above 0.30 m, the tendency to reduce the drop height became more marked until at the highest platform position (0.90 m) the actual drop height was equivalent to the previous nominal drop height (0.75 m). It would therefore appear that previously published results may also have been influenced in this way. Even allowing for the potential errors associated with using time of flight for the calculation of jump height it would still appear that to attain optimum rebound jump performance, the preferred dropping height could be anything from 10 cm to 75 cm and that different subjects achieved their best jumping performances from a wide range of different dropping heights.

To complete the analysis of the jump data, jump height performances for each subject in group B for the eight types of jump were plotted against calculated drop height. For the counter movement jumps the drop height was regarded as zero. To enable the squat jump data to be plotted on the same graphs an arbitrary height of -0.20 m was selected, (Figures 3.13a and 3.13b). This was used for display purposes only. The graphs in figure 3.13a show that all the male subjects produced their best jump performance when preceded by a counter movement. That is the subjects all jumped highest when performing a standard vertical jump. In addition the range of performances following a drop jump was remarkably consistent whether dropping
Figure 3.11. Quintic Spline fit of Calculated Drop Height plotted against Height.

Figure 3.12. Male and Female Nominal and Calculated Drop Height.
from a nominal height of 0.15 m or from 0.90 m. In all cases the jump from the static squatting position resulted in a low height jump. For half the subjects there were no differences between the squat jump performance and many of their corresponding drop jump performances and all subjects achieved either the lowest or second lowest height when performing the squat jump technique.

The female data presented in figure 3.13b, show different patterns to those for the male subjects. In particular, the counter movement jump only resulted in the best height jump in two cases. In four cases the best performance occurred as a result of a drop from a height of greater than 0.4 m. Subject SM showed an almost flat response across all conditions.

The first five subjects appeared to demonstrate the previously reported trend of increasing height jump performance as drop height increased until the dropping height exceeded 0.6 m. Subject EF was unusual in that she was the only one to drop from heights greater than the nominal platform height. That is she jumped upwards from the platform at takeoff. She also appeared to improve her subsequent jump height throughout the range of dropping heights at least until a drop height of 0.8 m had been reached.

A variety of items provided evidence to suggest that the male and female subjects responded in different ways to the task. To investigate this further an analysis of variance was conducted. Initially the male and female data were treated separately. A two way analysis of variance across six subjects for eight jump conditions was applied. Post hoc Tukey tests were then use to investigate cell mean differences. Table 3.7a summarises the ANOVA table for the male data, with the full breakdown appearing in Appendix 3.2a.

Table 3.7a. Male Data: Two way ANOVA: jump types and subjects.

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>df</th>
<th>Variance</th>
<th>F</th>
<th>F_0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1 (Subjects)</td>
<td>0.0322</td>
<td>5</td>
<td>0.0064</td>
<td>18.37**</td>
<td>3.60</td>
</tr>
<tr>
<td>Factor 2 (Jumps)</td>
<td>0.0262</td>
<td>7</td>
<td>0.0037</td>
<td>10.68**</td>
<td>3.21</td>
</tr>
<tr>
<td>Residual</td>
<td>0.0123</td>
<td>35</td>
<td>0.0004</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Significant at the 1% level.

Post hoc Tukey tests revealed that the differences between CMJ were significant at p=0.01 between SJ and DJ90. SJ was different (p=0.01) to DJ30 and DJ60. At the p=0.05 level of significance DJ45 and DJ75 were different to CMJ and SJ was different to all drop jumps from nominal heights of 0.30 m to 0.75 m. There were no significant differences between any of the drop jumps at either level of significance. The female data (Table 3.6b) showed less variation than the male data between CMJ and SJ and all other jump types at the 1% level of significance. At the 5% level DJ15 was different to DJ45 and DJ60.
Figure 3.13a. Male data for jumps CMJ, SJ, DJ15, DJ30, DJ45, DJ60, DJ75 and DJ90.
Figure 3.13b. Female data for jumps CMJ, SJ, DJ15, DJ30, DJ45, DJ60, DJ75 and DJ90.
Table 3.7b. Female Data: Two way ANOVA: jump types and subjects.

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>df</th>
<th>Variance</th>
<th>F</th>
<th>F&lt;sub&gt;0.01&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1 (Subjects)</td>
<td>0.0737</td>
<td>5</td>
<td>0.0147</td>
<td>53.39**</td>
<td>3.60</td>
</tr>
<tr>
<td>Factor 2 (Jumps)</td>
<td>0.0106</td>
<td>7</td>
<td>0.0015</td>
<td>5.46**</td>
<td>3.21</td>
</tr>
<tr>
<td>Residual</td>
<td>0.0097</td>
<td>35</td>
<td>0.0028</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Significant at the 1% level.

It therefore appeared that differences between the drop jumps were very minimal and so for a two way analysis of variance comparing all trials under each condition for both sexes, the eight jump groups were then re-categorised into five groups. The squat jumps and counter movement jumps remained unchanged, but the drop jumps were divided into three categories. Drops from nominal heights of 0.15 m and 0.30 m were averaged and treated as Low jumps (DJL). Drops from a Medium height platform (DJM) were those from nominal platform heights of 0.45 m and 0.60 m. Drops from a High platform (DJH) were made from nominal platform heights of 0.75 m and 0.90 m. The calculated drop heights for the three drop jump categories reported in Table 3.8 show that the mean drop heights were similar for male and female groups, although the variation in the male data was greater than for the female data.

Table 3.8. Calculated Drop Jump Heights for male and female subjects.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MALE</td>
<td>MEAN</td>
<td>STDEV</td>
<td>FEMALE</td>
<td>MEAN</td>
<td>STDEV</td>
</tr>
<tr>
<td>DJL</td>
<td>0.23</td>
<td>±0.06</td>
<td>DJL</td>
<td>0.23</td>
<td>±0.05</td>
</tr>
<tr>
<td>DJM</td>
<td>0.47</td>
<td>±0.13</td>
<td>DJM</td>
<td>0.50</td>
<td>±0.06</td>
</tr>
<tr>
<td>DJH</td>
<td>0.76</td>
<td>±0.11</td>
<td>DJH</td>
<td>0.77</td>
<td>±0.07</td>
</tr>
</tbody>
</table>

To maintain equal group sizes the data for the first six female subjects and all the group B male subjects were included. Reversing the sequence of performing the jump trials reduced the influence of order effects due to fatigue, experience and boredom. Randomness was assumed and homogeneity of variance in the samples was checked by dividing the largest by the smallest subgroup variances to determine an F<sub>max</sub> value. (Table 3.8a).

Table 3.8a. Homogeneity of Variance Check for male and female CMJ, SJ, DJL, DJM and DJH trials.

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th>SJ</th>
<th>DJL</th>
<th>DJM</th>
<th>DJH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male Variance</td>
<td>0.0010</td>
<td>0.0018</td>
<td>0.0011</td>
<td>0.0012</td>
<td>0.0013</td>
</tr>
<tr>
<td>Female Variance</td>
<td>0.0032</td>
<td>0.0037</td>
<td>0.0042</td>
<td>0.0034</td>
<td>0.0049</td>
</tr>
</tbody>
</table>

Maximum and Minimum Variances Underlined

F value = \( \frac{\text{VAR}_{\text{max}}}{\text{VAR}_{\text{min}}} = 4.775 \) \( (F = 5.0503 \text{ at } p=0.05) \)
The calculated value of 4.775 was smaller than the F statistic \((F = 5.05)\) at the 5% level of significance and therefore confirmed the assumption that the groups had similar and homogeneous variances. A small sampled two way Analysis of Variance (ANOVA) was therefore used to investigate the differences between the subjects' performances in the different styles of jump. The first factor had two levels, male and female. The second factor, jump type, had five levels. A repeated measures design was used since the same subjects performed all the jumps, (CMJ, SJ, DJL, DJM, DJH). There was no significant difference between the performances of the male and female groups, (Factor 1 in Table 3.8b).

Table 3.8b. Two Way ANOVA with repeated measures: Summary table for male and female CMJ, SJ, DJL, DJM and DJH trials.

<table>
<thead>
<tr>
<th>Factor</th>
<th>SS</th>
<th>df</th>
<th>Var</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR 1 (M/F)</td>
<td>0.0516</td>
<td>1</td>
<td>0.0516</td>
<td>3.69 (ns)</td>
</tr>
<tr>
<td>FACTOR 2 (JMP)</td>
<td>0.0207</td>
<td>4</td>
<td>0.0052</td>
<td>19.37 (**)</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.0027</td>
<td>4</td>
<td>0.0007</td>
<td>2.48 (ns)</td>
</tr>
<tr>
<td>Between Error</td>
<td>0.1399</td>
<td>10</td>
<td>0.0140</td>
<td></td>
</tr>
<tr>
<td>Within Error</td>
<td>0.0107</td>
<td>40</td>
<td>0.0003</td>
<td></td>
</tr>
</tbody>
</table>

Also there was no significant interaction effect between gender and jump type. However, the differences between the five jump types was highly significant with \(F = 19.37, (F = 3.83 \text{ at } p=0.01)\). A post hoc Tukey test was conducted to investigate the differences between the five jump types, Table 3.8c.

Table 3.8c. Tukey post hoc test of jump type mean differences.

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th>SJ</th>
<th>DJL</th>
<th>DJM</th>
<th>DJH</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMJ</td>
<td>0.3826</td>
<td>0.0748**</td>
<td>0.0368**</td>
<td>0.0315**</td>
<td>0.0427**</td>
</tr>
<tr>
<td>SJ</td>
<td>0.3078</td>
<td>-0.0380**</td>
<td>-0.0434**</td>
<td>-0.0322**</td>
<td></td>
</tr>
<tr>
<td>DJL</td>
<td>0.3458</td>
<td>-0.0053</td>
<td>0.0059</td>
<td>0.0112</td>
<td></td>
</tr>
<tr>
<td>DJM</td>
<td>0.3511</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DJH</td>
<td>0.3399</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Differences between the means were significant at \(p=0.01 (**\) when they were greater than the Tukey 'T' value of 0.0234. Calculation of the 'T' value was based on the percentage point \((q)\) for 5 means and 40 degrees of freedom in the Tukey Test table from Pearson and Hartley (1966). The error variance \(V\), and group size \(N\) were used with \(q\) in equation 3.4.

\[
T = (q) \times \text{SQRT} \left( \frac{V}{N} \right)
\]

All the differences that were observed were significant at the 1% level. Counter movement jumps were different to all other types of jump and squat jumps were significantly different to
the three drop jumps. There were no significant differences between the drop jumps performed from low heights (<0.25 m), medium heights (0.50 m) and high heights (>0.75 m). This latter observation contradicts previously published results (e.g., Asmussen and Bonde-Peterson, 1974a) who found an optimum performance in rebounding jump height when drops were made from a height of approximately 0.4 m.

3:3.3 DISCUSSION

A number of interesting points were produced by the analyses. Flight-time was found to be a good predictor of take-off velocity providing that:

a. the time resolution was small, (0.002 s), and
b. the flight time was determined directly from a digital signal.

All counter movement and drop jumps resulted in greater jump heights than were achieved from a squat jump which is in agreement with previously published research, (Asmussen and Bonde-Peterson, 1974a; Komi and Bosco, 1978a). Cavagna et al. (1971) stated that there were no differences between the jumps with and without a counter movement. However, Asmussen and Bonde-Peterson (1974a) re-analysed Cavagna's data and stated that the jump heights attained following a counter movement were just over 11% greater than those from the squat jump (males and females combined) which was more than twice the 5% increase that they had found with their own data. The corresponding comparison for the Komi and Bosco (1978a) study was 13% although the male and female subjects responded differently, (male physical education students = 14%, female physical education students = 21% and male volleyball players = 17%). This was opposite to the findings of the current study where the male subjects showed a 25% improvement compared to that of 11% for the females. The female subjects in Komi and Bosco's (1978a) study jumped considerably lower in both jumping styles than the female subjects in the other two studies with a mean SJ of 0.192 m compared with 0.255 m and 0.291 m, and a CMJ of 0.233 m compared with 0.395 m and 0.403 m. It was also noticeable that the group of specialised jumpers (male volleyball players) in Komi and Bosco's (1978a) study jumped higher than the other male subjects. It would therefore appear that there may be a skill element in drop jumping which influences the findings, which is therefore dependent on the subjects used. It would also appear that whatever benefit is gained from a counter movement, whether from standing or following a drop, the resulting increased jump height over a squat jump does not appear to be subject or skill specific.

In drop jumping, modification of the apportionment of the total ground reaction impulse lead to a more realistic estimate of drop heights. Calculation of drop heights from impulse also reduced the true range of the drop heights used by subjects. Using a quintic spline procedure provided a
method for direct comparison of individual subject performances by allowing for non-
standardised drop heights to be included. It also highlighted an attenuating effect on the data.
As drop height increased the differences between the calculated and nominal drop heights grew
with the variation being highly significant at the top end of the range, \((p<0.01)\). There was a
very limited range of jump heights. The implications of this finding are particularly relevant to
people using plyometric (variations on drop jumping) training procedures. The ‘optimal
training’ drop heights quoted by (Asmussen and Bonde-Peterson 1974a; Bosco and Komi,
1978a) were not obvious. In fact drop heights within a very broad range between 0.10 m and
0.70 m, all resulted in similar jump height performances. There was little evidence in support of
an ‘ideal or optimum’ height being prominent. Asmussen and Bonde-Peterson (1974a),
although generally supporting the idea that their subjects improved their performances following
the drop jump, stated that some gained nothing and one of their subjects performed worse when
jumping down from a height. A similar finding was obtained in the current study with one third
of the male subjects and half of the female subjects jump performances failing to match the
expected optimum performance when dropping from a height of approximately 40 cm. Two
previous studies (Asmussen and Bonde-Peterson, 1974a; Komi and Bosco, 1978a) concluded
that jump heights following a drop from a mid range height (0.4 m to 0.6 m) produced a better
jump height than was obtained from a counter movement jump. Bedi et al. (1987), however
found that there were no differences between the jump heights attained from any drop height
and that counter movement jumps always resulted in higher jumps than drop jumps. This is in
agreement with the current study and in contradiction with the findings of the previous two
studies.

As expected the variability in the individual performances produced no useful outcome and
when all the subject data were combined for males and females and for all drop heights the
resulting regression analysis resulted in a virtually flat response over the complete range of drop
heights tested. Subjects responded in different ways and so an individual’s performance was
unpredictable.

3:4 SUMMARY

Examination of squat, counter movement and drop jumping tasks was undertaken to examine
the influence of the stretch-shortening cycle on jump performance. Enhancing the effective time
resolution of the force sampling processes has been shown to be effective in improving the
accuracy with which mass centre velocity at takeoff for a vertical jump could be determined.
Improvements in the force plate mounting were required before the benefits of increasing
overall force quantisation and force sampling rate could be capitalised upon. The need for
further investigation of the laboratory force plate mounting and in particular in the frequency
response characteristics of the combined force plate and mounting were highlighted. The lack
of precision in apportioning the landing, support and takeoff impulses and the whole question of
gaining benefit from the stretch-shortening cycle needed further consideration. Counter
movement and drop jumps produced higher jumps than squat jumps, but there was no clear
evidence for an optimal drop jump height. Counter movement jumps resulted in higher jump
heights than drop jumps in all cases. This is in agreement with Bedi et al (1987) but in conflict
with Asmussen and Bonde-Peterson (1974a) and with Komi and Bosco (1978a). The idea of
quantifying the contribution from elastic structures in the body to rebound jumping activities
with the simple rebound model proposed by Asmussen and Bonde-Peterson (1974a) and Bosco
and Komi (1978a), although appealing in its simplicity proved to be of little value in gaining
insight into this problem.

The need to study the motions of the limbs with a view to apportioning segmental contributions
to jump performance meant that cinefilm or video had to be combined with force plate data.
This brought further questions concerning the selection of appropriate framing rates and force
sampling procedures. Chapter 4 details the visual image calibration and force sampling data
specification required for a second vertical rebound jumping study described in Chapter 5.
Although the current study has highlighted the need to improve the quality of the force data
required to describe the jumping action, Hay et al. (1978), argued that the jumping actions
described by Komi and his co-workers were far from "simple" and that an improved
understanding of two segment motions was required before the complexity of jumping could be
investigated with any confidence. The desire to better understand the segmental contributions
in jumping lead directly to the combined visual and force analysis experiments described in
Chapter 5.
CHAPTER 4

FORCE DATA AND VISUAL IMAGING CALIBRATION

4:1 INTRODUCTION

This chapter is preliminary to an experimental study on rebound jumping reported in Chapter 5. Force and visual image data were required to quantify the action of jumping and so a series of preparatory experiments were undertaken. From the results of these experiments a full specification of the force and visual imaging requirements were defined.

The purpose of this chapter was to answer the following questions:

(i) what were the frequency characteristics of the force plate and its mounting in the laboratory?

(ii) was the force plate mounting in the laboratory suitable for the jumping experiments that were planned?

(iii) what was the accuracy of the force plate, amplifier and computerised data capture system?

(iv) what was the measurement accuracy of cinefilm and video tape and their associated digitisation procedures?

(v) which visual image recording system was most suitable for the planned study of rebound jumping?

Question (i) has been answered using a mechanical engineering technique known as modal analysis. Question (ii) has been answered using a combination of modal analysis and previous research on the frequency content of human movement (Kerwin and Chapman 1988b). A series of static and dynamic calibration loading tests to check magnitude and point of force application on the plate have been used to answer Question (iii). The associated electronics and computerised data capture systems were checked within these tests. Question (iv) required recording and digitising of a calibration grid using cinefilm and a combination of video systems, the outcome of which enabled question (v) to be answered.
4:2. FORCE PLATE MODAL ANALYSIS

4:2.1 INTRODUCTION

The force plate and its mounting form a mechanical system, which when impacted will vibrate. If during a human impact landing, vibrations were excited in the force plate and its mounting which fell within the frequency spectrum of the recorded data, it would be impossible to identify these. The natural frequencies, or resonances, of the force plate and its mounting were therefore identified independently using an engineering technique known as modal analysis.

4:2.2 METHOD

Introduction

The lowest resonant frequency for a force plate of the type used (Kistler 9281B12) is reported in the manufacturer's calibration literature to be around 750 Hz, but applies to the plate alone. Under ideal circumstances, and following the recommendations from the manufacturer (Kistler Instruments, UK Ltd), a force plate mounting frame should be grouted into a concrete foundation block of large mass which is insulated from the surrounding floor. Local conditions in the biomechanics laboratory prevented the use of such a construction. In particular, the water table at the site of the laboratory was too high to facilitate a sunken mounting. A surface mounting was therefore chosen. This has been referred to as mounting frame condition A. The remaining mounting frame condition (B) used a solid steel base plate, manufactured from a machine tool base, which was surface mounted in the laboratory.

Force Plate Mountings

The standard mounting frame (Kistler 9423), comprises four steel corner pillars with plane top faces connected by steel sectional links braced at the corners with diagonal tights. This structure was designed for immersion in a concrete grouting material. For surface mounting (condition A) the cross links were drilled and the whole frame secured to the floor of the laboratory, using masonry bolts, as shown in Figure 4.1a. A surrounding wooden box with a central opening just large enough to accommodate the force plate was constructed. This had twin angled brackets attached on opposite sides to enable the whole unit to be bolted to the floor. Any horizontal movement of this, or the remaining walkway boxes, was thus prevented from being transmitted to the force plate. When the force plate was bolted to the mounting frame is became clear that the plane surfaces of the mounting frame pillars and their counterparts on the base of the force plate could not be perfectly matched. Metal shims of thickness 0.010" and 0.020" were provided by the manufacturer to allow for minor level variations, but it was impossible to secure
Figure 4.1. (a) Plan view of Kistler mounting frame bolted to the surface of the laboratory floor. (b) Side elevation of mounting frame with spacers in position below cross members to reduce bending under compression.

Figure 4.2. Force plate and solid metal base plate with locating pegs and bolted force plate, set within raised wooden walkway.
the frame to the laboratory floor without some distortion in the plane surfaces. Additional steel spacers (washers) were used as packing to support the lower surfaces of the mounting frame cross braces, (Figure 4.1b) but securing the frame was inconsistent.

A second option was therefore experimented with, (frame condition B). A solid steel mounting block of dimensions 0.395 m x 0.595 m x 0.050 m and mass 80 kg was cut from a machine tool base plate. Eight holes were drilled, four in the top surface were tapped to match the thread requirements of the force plate transducer mounting points (10 mm) and four in the lower surface to accommodate locating pegs which slotted into corresponding holes drilled in the concrete laboratory floor. The floor holes were not tapped and so the locating pegs simply lowered as a tight fit into the holes to prevent horizontal slippage, (Figure 4.2). This prevented the application of torque to the mounting base plate and ensured that the machined surface of this solid mounting frame remained planar.

An outdoor site for the force plate was constructed at the athletics stadium as shown in Figure 4.3. The foundation block and mounting installation were designed to meet the manufacturer's recommendations, (Kistler Instruments, UK Ltd). A 2.2 metric tonne block of concrete was constructed on a shale base and insulated from the remaining track foundations at surface level using a retaining steel frame. A 2.5 mm gap was provided around the force plate separating it from the main track surface. Underground waterproof trunking (Covex tubing) was laid to carry the charge amplifier cable from the force plate to a small outlet beyond the perimeter of the track. A resin based concrete grouting (Cranfield University) was used to install the standard mounting frame, (frame condition C). The resin grouting was selected to prevent shrinkage and expansion as weather conditions varied throughout the year and provided a smooth and non-porous finish to the visible part of the installation.

**Modal analysis**

Modal analysis is a standard procedure used in engineering to determine the frequency characteristics of a mechanical system. The force plate as a unit, comprising a top plate and four transducers, is routinely tested by the manufacturer prior to distribution and its natural frequency listed in the accompanying calibration report. However, the plate when on its mounting, becomes a unique mechanical system. The frequency response of this combined unit therefore needed to be determined. Three modal analysis tests were conducted:

- Frame Condition A - plate on the standard frame (Kistler 9423) bolted to the floor
- Frame Condition B - plate on the new solid base plate surface mounted on the floor
- Frame Condition C - plate on the standard (Kistler 9423) frame grouted in resin*

(*The standard grouted mounting could only be installed at the stadium site)
Figure 4.3. Outdoor force plate mounting showing cross section of the foundation block, resin grouted mounting frame and cable ducting.

Figure 4.4. Modal analysis of the force plate with an accelerometer mounted at location (-50,100) and a 50 mm hammer impact grid pattern.
Tests on frame condition A were initially undertaken with the frequency range limited to 1kHz (test A1 in table 4.2, but following preliminary tests at site C, where minimal response was detected below 1000 Hz, the frequency range for all tests was increased to 2kHz. In all three cases the testing procedures in the vertical direction (Z) were the same. A test mesh of intersecting lines at 0.05 m intervals was drawn on the top surface of the plate. Tests A and B were carried out in the laboratory and test C was conducted at the athletics stadium. The method adopted used an instrumented hammer to deliver force impulses to the matrix of coordinates mapped out by the mesh for half the plate surface. A single surface mounted accelerometer detected the accelerations generated by the series of force impulses (Figure 4.4). The time histories of the force impulses and induced accelerations were recorded on a dual channel fast Fourier analyser (Nicolet, 660A Fast Fourier Analyser) capable of dealing with transient responses. Two separate tests were conducted with the detecting accelerometer mounted in different locations (-100,50 and -50,250) to ensure that all modes were identified.

Frequency spectra were obtained for the measured variables and then processed to display the imaginary components of the derived transfer function, obtained by the division of the acceleration spectrum (the response) by the force spectrum (the excitation). The imaginary component of the transfer function gave a measure of the phase and amplitude of motion of discrete points on the force plate for all frequency spectrum lines. The real part of the spectrum indicated whether there was a phase difference of 0° or 180° between the displacement of the mass and the excitation force. The frequencies, at which the imaginary component was a maximum, identified a condition when the amplitude of response had a phase difference of 90° or 270° to the input force excitation and so were coincident with the resonant frequencies associated with the force plate. If the detecting accelerometer had been positioned over a nodal point for a particular frequency, that is a point where no displacement would occur, a particular resonance would have been identified. This was obviated by the use of a second location for the detecting accelerometer. The use a minimal number of accelerometer locations with multiple instrumented hammer impact locations is the preferred option in modal analysis. The alternative of moving the accelerometer over the grid pattern and re-attaching it securely at each site is less convenient. By the Reciprocal Theorem (Benham and Warnock, 1973) either option produces the same results. The use of two accelerometer locations ensured that resonances which may have been missed if hammer impacts had been applied at nodal points was similarly avoided.

The primary modes of vibration which were studied included vertical solid body motion (translation in the Z direction) and rocking about the horizontal axes X and Y. In addition, the modal analysis was extended to investigate torsion about the vertical axis (Z), plate bending and solid body motion along the horizontal X and Y axes. The accelerometer was moved to one of the outer edges of the XZ face of the plate and impulses were applied along the opposing XZ face of the plate. A similar procedure was conducted with the accelerometer and hammer
impacts being sited on opposing YZ faces of the force plate. These latter two tests were only possible in tests A and B. At the athletics stadium site the vertical faces of the plate were below ground level and therefore not accessible for mounting the accelerometer or delivering hammer impacts.

Theoretical analysis of the plate and ideal mounting

A theoretical analysis was conducted to relate the solid body and rocking motions of the force plate that might be expected from a symmetrical corner mounted stiff beam structure.

If the force plate is represented as a solid body mass on four mounting posts represented as stiff springs, the vertical motion of the plate can be described as simple harmonic and specified by equation 4.1. The plate is shown as a beam of mass (m) supported on four springs of stiffness k, as shown in Figure 4.5. The springs are shown as parallel pairs of stiffness 2k. Displacement in the vertical direction (Z) represents one of the possible motions for this system. Clearly rocking and bending are also possible.

Theoretical predictions of solid body motion and rocking are presented for comparison with experimental data to check that the nature of the vibrations identified by the modal analyses produced results which were in keeping with theoretical expectations.

For a linear spring, the restoring force (F) is proportional the displacement (z) and acts in the direction opposite to the motion. The equation for solid body motion of this structure would be:

\[ F = m \cdot a \]
\[ F = m \cdot \ddot{z} \]
\[ -k \cdot z = m \cdot \ddot{z} \]

\[ \ddot{z} + \left( \frac{k}{m} \right) \cdot z = 0 \]  
4.1

\[ z = A \cos \omega t + B \sin \omega t \]  
4.2

Substituting z from 4.2 into 4.1

\[ -\omega^2 (A \cos \omega t + B \sin \omega t) + (k/m) (A \cos \omega t + B \sin \omega t) = 0 \]

for motion to occur (A \cos \omega t + B \sin \omega t) must not equal zero and therefore

\[ \omega = \sqrt{\frac{k}{m}} \text{ rad} \cdot \text{s}^{-1} \]
Figure 4.5. Representation of force plate, of mass $m$, as a beam mounted in four linear springs of stiffness $k$, oscillating in the direction $z$.

Figure 4.6. The Principal axes and dimensions of the force plate used in a theoretical analysis of rocking natural frequency.

\[ I_x = \frac{m}{12} (h^2 + l_y^2) \]
\[ I_y = \frac{m}{12} (h^2 + l_x^2) \]

where $I_x$ and $I_y$ = Moments of Inertia of the plate about axes $X$ and $Y$, $m$ = mass of plate, $h$ = thickness of plate (0.0475 m), $l_y$ = 0.600 m and $l_x$ = 0.400 m. The moment arms are the distances from the load cells to the $X$ and $Y$ axes, 0.200 m and 0.120 m respectively.
In Figure 4.6 there are four springs, each of stiffness k, and so given that frequency \( f = \omega / 2\pi \), the expression for the natural frequency of the plate \( f \) would be given in equation 4.3.

\[
f = \frac{1}{2\pi} \sqrt{\frac{4k}{m}} \]

4.3

Similarly an expression for the rotational frequency \( f_r \) of the beam about the two principal axes \( X \) and \( Y \), (Figure 4.6) can be obtained. Using the angular equivalent of the restoring force and the moments of inertia for the respective axes in equation 4.3, the corresponding rotational frequencies for the beam about the \( X \) and \( Y \) axes can be found. In equation 4.4, \( k_1 \) represents the rotational stiffness of the spring at distance \( l \) from the respective \( X \) and \( Y \) axes. Moments of inertia of the beam \( I \) can be found using the equations shown in Figure 4.6.

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{4k_1(l)}{I}} \]

4.4

Plate mass and support pillar stiffness data were taken from the equipment manufacturer's literature, (Kistler Instruments UK, Whiteoaks, The Grove, Hartley Whintney, Hants, RG 27 8RN).

4:2.3 RESULTS

Modal analysis of the plate and mounting

Modal analysis tests confirmed the earlier observation that the frame could not be bolted consistently or satisfactorily and therefore modification to the mounting frame was required. Theoretical analysis of the plate and mounting, based on the assumption that the plate can be modelled as a solid rectangular beam supported by four identical springs was carried out.

Theoretical modal analysis

Using equation 4.3, with \( k = 10^8 \) N/m, and \( m = 42 \) kg, the theoretical natural frequency of the plate in the vertical direction would be:

\[
f^2 = 1/4\pi^2 (4 \times 10^8/42) \\
f = 491.2 \text{ Hz}
\]

The moments of inertia of the plate about the \( X \) and \( Y \) axes were calculated, assuming constant density, from the equation for a solid rectangular block to be:
\[ I_x = \frac{M}{12} (h^2 + l_x^2) = \frac{42}{12} (0.0475^2 + 0.600^2) = 1.2679 \text{ kg} \cdot \text{m}^2 \]

\[ I_y = \frac{M}{12} (h^2 + l_y^2) = \frac{42}{12} (0.0475^2 + 0.400^2) = 0.5679 \text{ kg} \cdot \text{m}^2 \]

Using equation 4.4, with the above stiffness, mass and moment of inertia values the rocking natural frequencies were calculated to be:

\[
f_{rx} = \frac{1}{2\pi} \sqrt{\frac{4k_r \cdot I_y}{I_x}}
\]

\[f_{rx} = 0.1592 \sqrt{4 \times 10^8 \times 0.200/1.2679} \]

\[f_{rx} = 565.38 \text{ Hz} \]

\[
f_{ry} = \frac{1}{2\pi} \sqrt{\frac{4k_r \cdot I_x}{I_y}}
\]

\[f_{ry} = 0.1592 \sqrt{4 \times 10^8 \times 0.120/0.5679} \]

\[f_{ry} = 507.87 \text{ Hz} \]

Thus using vibration theory and considering the plate as a solid rectangular beam mounted on four identical linear springs, it has been shown, that for the Kistler plate, the frequency ratio of translational resonance along the Z axis : rocking about the Y axis and rocking about the X axis should be:

0.97 : 1.00 : 1.12

These values are in general agreement with previously reported experimental results by Kerwin and Chapman (1987), where the first three resonances obtained were 525 Hz, 650 Hz and 745 Hz respectively giving a corresponding set of ratios of

0.81 : 1.00 : 1.15.

These values are clearly different, but the order of the frequency modes is in agreement with the theoretical predictions, and as the real plate is not a simple rectangular solid beam, this is expected.
**Experimental modal Analysis**

Ewins (1985), stated:

*The power of this analytical technique, known as modal analysis, is that the magnitude and sense of the imaginary components indicate the amplitude of the motion, at the application of the impulse force, for all resonant frequencies in the range under investigation. Ewins, 1985.*

Figure 4.7 shows a sample output plot of the imaginary components of the frequency spectrum for the range 0 to 2 kHz for Test C. The plot shows the mean data for eight excitation impacts applied at location (+200,+300) with the accelerometer in location (-100,+50). Strong resonances were apparent at 860 Hz and 1125 Hz. The mode shape for the 860 Hz natural frequency is shown as image (e) in Figure 4.9. This shape was constructed by locating the peaks in the imaginary spectrum at 860 Hz. Initially the deflection at the extreme edge point (-200,300) was negative. By tracking towards the centre of the plate, along the 860 Hz line, the amplitude increased until it reached a maximum in the middle of the plate (-200,0). A similar pattern was detected along the mid line of the plate (0,300 to 0,0) and along the positive X edge (200,300 to 200,0). The plate was clearly bending with its peak amplitude along the mid line (principal X axis). It had a nodal line somewhere between Y=200 and Y=250, that is just beyond the location of the transducers, and showed its minimum deflection along the axis parallel to the principal X axis passing though the value Y=300. Three other notable resonances at 1125 Hz, 1695 Hz and 1940 Hz were detected for the plate on mounting C. When mounting B was studied, that is with the plate secured to the solid metal machine base in the laboratory, resonances starting at 520 Hz were detected.

The data for the plate in condition A (the bolted frame in the laboratory) were more varied and contained lower natural frequencies. Variations in the tightness of the securing bolts changed the lowest natural frequency detected from 390 Hz to 420 Hz for solid body motion in the vertical (Z) direction. Rocking about the Y axis ranged from 460 Hz to 780 Hz. A list of observed frequencies and associated mode shapes, as identified in Figure 4.9, for the three tests are presented in Table 4.1. The mode shapes are identified by combining a series of imaginary component outputs as shown in Figure 4.7 over a range of excitation sites and then joining the peak of the imaginary components at each frequency waterfall plot (shown in Figure 4.8) to determine the displacement characteristics of the plate. The output plots, although shown as continuous graphs, are digital in nature and represent 400 discrete frequencies in the range 0 to 2kHz. The resulting resonances are approximations to the nearest 5Hz (2000/400). The associated mode shapes will similarly be approximations based on these integer frequencies. From Table 4.1, it can be seen that under frame condition A, natural frequencies well below the plate's expected minimum of approximately 750 Hz were apparent.
Figure 4.7. Plot of the imaginary component (I) for the mean of 8 transfer functions (TF).

The scale of the Imaginary component, plotted on the vertical axis, was determined automatically within the spectrum analyser. The location of the peaks on the horizontal axis enabled the resonant frequencies to be detected.

Figure 4.8. Waterfall plot showing imaginary components plotted against frequency along three parallel YY axes.

Note for this illustration, data for impacts across half the plate surface have been included, (ie X ranging from -200 mm to +200 mm, Y ranging from 0 mm to +300 mm)
Figure 4.9. Force plate resonant mode shapes.

(a) and (h) = solid body motion in the Z direction
(b), (e), (f1), (f2), (g), (i1) and (i2) = plate bending
(c) and (d) = rocking about Y and X axes respectively
Table 4.1. Identified resonant frequencies for a Kistler 9281B12 force plate on three different mounting frames A, B and C at two test sites.

<table>
<thead>
<tr>
<th>Test Site</th>
<th>Laboratory A1</th>
<th>Laboratory A</th>
<th>Laboratory B</th>
<th>Athletics Stadium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mode</td>
<td>(Hz)</td>
<td>(Hz)</td>
<td>(Hz)</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>525</td>
<td>390</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td></td>
<td>420</td>
<td>535</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>535</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>590</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>650</td>
<td>460</td>
<td>730</td>
</tr>
<tr>
<td></td>
<td></td>
<td>465</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>780</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>745</td>
<td></td>
<td>870</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>895</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>990</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>880</td>
<td>880</td>
<td>870</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900</td>
<td>945</td>
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<td></td>
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<td>950</td>
<td>980</td>
<td>990</td>
</tr>
<tr>
<td></td>
<td>f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>g</td>
<td></td>
<td>1255</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1280</td>
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<td>1360</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1480</td>
<td></td>
</tr>
<tr>
<td></td>
<td>h</td>
<td></td>
<td>880</td>
<td>1690</td>
</tr>
<tr>
<td></td>
<td>i</td>
<td></td>
<td>1170</td>
<td>1940</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1880</td>
<td>1940</td>
</tr>
</tbody>
</table>

limit of frequency range =1kHz 1015

limit of frequency range = 2kH

Mounting A1: plate on the standard frame (Kistler 9423) bolted to the floor (1kHz range)
Mounting A: plate on the standard frame (Kistler 9423) bolted to the floor
Mounting B: plate on the new solid surface mounted frame
Mounting C: plate on the standard (Kistler 9423) frame grouted in resin

Modes shapes a to i refer to images in figure 4.11 and were constructed using the waterfall plots, as shown in figure 4.10, of imaginary components plotted against frequency. Half the plate surface was analysed and then the shapes reflected in the X axis to form the whole plate mode shape.
4:2.4 DISCUSSION

When located on an ideal solid concrete mounting (C), the characteristics of the plate predominate. The manner in which the force plate was bolted to the frame under each condition remained consistent and relied upon the use of a torque wrench to ensure uniformity and consistency of bolt tension. It also indicates that the method resulted in a very rigid attachment since the resonance of the ideal plate and mounting is virtually identical to the plate alone. In the laboratory, where surface mounting was necessary, the same rigidity of attachment between the plate and the frame was used, and so the shift in the natural frequency range of the combined structure indicates a lack of rigidity in the contact between the frame and the floor. Using a relatively loose contact between the bolted frame condition (A) and the floor produced the results shown in Table 4.1 A. A more secure bolting of the original frame resulted in the results shown in Table 4.1 A, and the use of the newly designed solid mounting frame condition (B) consistently produced the results reported in Table 4.1 B. Bearing in mind that the force plate and its mounting are moved around the laboratory and that modal analysis is not readily available, frame condition B was selected as the preferred option in what was a less than ideal surface mounting arrangement. This combination of mounting frame and force plate provided a consistent frequency response without the need for adjustments or modifications to the mounting and was therefore deemed suitable for the dynamic jumping tests which were to follow. However, changing the mounting frame from that recommended by the manufacturer, may also have changed other characteristics about the plate. Its frequency characteristics had been characterised by the modal analysis tests, but its accuracy under static and dynamic loading conditions needed to be checked. In addition, the data recording equipment, including the computerised analog to digital converter, needed to be included in the calibration of the system.
4:3 FORCE PLATE CALIBRATION AND DATA SPECIFICATION

4:3.1 INTRODUCTION

Force plates have been used extensively in biomechanics research but since standardised commercially manufactured plates have been adopted almost universally, details of accuracy and measurement limitations are not often reported. Antonsson and Mann (1985) and Bobbert and Schamhardt (1990) are recent exceptions. Both studies focussed on the dynamic characteristics of the plate, with the former concentrating on the frequency response of a plate of similar dimensions to the one used in the current study (0.600 m x 0.400 m) and the latter on the effects of impact loadings on the accuracy of point of force application data on a plate of larger overall size (0.900 m x 0.600 m).

As a result of the modal analysis tests, the newly constructed solid machine tool base plate was selected as the preferred force plate laboratory mounting. A set of calibration experiments, which combined static and dynamic tests, were carried out to ensure that the force plate, with its associated electronic amplification unit and computer interface, were still operating within acceptable limits and within the manufacturer's specified tolerances, (Kistler Instruments, UK, Ltd and Cambridge Electronic Design). The static tests included incremental loading and unloading of the plate and point loading with fixed weights at varying positions on the plate's surface. The dynamic tests comprised a series of impacts at varying positions across the surface of the plate. The latter tests were particularly important since the dynamic characteristics of the plate and new mounting (frame condition B), although superior to the original surface mounted bolted frame and plate combination (frame condition A), were still not ideal in that they did not match the manufacturer's recommendations (frame condition C). The modal analysis had characterised the frequency responses of the plate on its new mounting, but did not provide information on how the point of force application might be affected by this new installation.

4:2.2 METHOD

Introduction

All data were collected using the standard force plate and amplifiers, (Kistler 9281B12 and 9851 respectively). Outputs from the amplifiers were taken via an analog to digital converter, (ADC, CED1401 laboratory interface) to a computer (Acorn BBC Master 128k). The calibration test series has been divided into three sections; including calibration of the force plate, force data sampling, and data synchronisation. The calibration section examined magnitude and point of force application accuracy under three sub-headings; incremental loading, static point of force loading and dynamic point of force loading.
Calibration - magnitude and point of force application

Incremental loads

Incremental loads from zero Newtons up to 1200 Newtons, in 100 Newton steps, were applied to the force plate. Four sets of data were sampled for one second at 250 Hz for each load. This process was repeated in reverse order during unloading. The electronics were reset between loads to ensure that charge amplifier drift effects were minimised. A linear regression analysis was used to check linearity and confidence intervals in measuring forces.

Static point of force application

Static loads of approximately 500 Newtons were placed on the force plate at the four corner sites, four mid line sites and at the centre of the plate, (details in Appendix 4.1b). Competition weight lifting discs, which had been previously weighed on a clinical scale (Herbert and Sons, Limited, Edmonton), were applied over the nine tapped holes in the surface of the top plate. A steel ball bearing of diameter 8 mm was placed into the tapped hole of interest. A pivoted steel beam was positioned above the ball bearing onto which the weights were applied. The net force acting on the plate varied between 200 N and 250 N. Data were sampled at 250 Hz for four seconds at each of the 35 sites for the standard six force plate output channels, (vertical force $F_z$, anterior posterior force $F_y$, medio-lateral force $F_x$, point of force application in the medio-lateral direction $a_x$, point of force application in the anterior posterior direction $a_y$, free moment about the z axis at the point of force application $M_z$). Mean and standard deviation values were calculated at each location. In addition root mean square (RMS) differences between these mean values and the known locations were calculated.

Dynamic point of force application

The point of force application tests were repeated under dynamic loading conditions. The tests were extended to include all 35 tapped holes on the plate's top surface as shown in Figure 4.10. A cantilevered steel beam was again used. This was positioned over a steel ball bearing and dynamic loads were applied by a subject (mass 74.2 kg) running across the plate. Foot contact forces were applied to the beam and hence transmitted to the single point on the force plate surface. Data were sampled on the standard six channels for each of the 35 sites at a frequency of 500 Hz. Mean, standard deviation and RMS values were determined for each point.
Figure 4.10. Location of dynamic point of force impacts.

Figure 4.11. Locations of Elliptical Error Zones for impact points on force plate surface.

The greyed dotted circles show the locations of the four load cells. The missing data set at point (-160, 160) is shown as a grey ellipse.
4.3.3 RESULTS

Magnitude and point of force application

Linear regression analysis of the static incremental loading resulted in a correlation coefficient of 1, (0.999996). Using the generated regression model it was possible to predict loadings from individual force values to ±10 N. The amplifiers had been set to the 5k range, that is 5000 N output = 10 V DC, and so the accuracy claimed by the manufacturer (Kistler Instruments, UK.) of <1% was comfortably achieved. (Additional details can be seen in Appendix 4.1a).

Static point of force application tests showed that the mean RMS error was 9 mm (±0.28 mm) at the corner points, and 6 mm (±0.17 mm) on the mid line. The accuracy claimed by the manufacturer was ±2 mm in x and y directions giving an RMS error of approximately 3 mm. This accuracy was only observed for about 30% of the points tested. Approximately 65% were within ±3 mm and just over 90% were within ±5 mm. (Further details of the results can be seen in Appendix 4.1b).

Dynamic point of force application tests resulted in a wide range of errors. The plate surface was divided into three zones. The outer 20 points formed the Perimeter, the central three points form the Central Zone and the remaining 12 points constituted the Mid Zone. Figure 4.11 shows the RMS errors as ellipses with the error in \( a_y \) forming the major axis and the error in \( a_x \) forming the minor axis. The four light grey circles indicate the size and location of the load cells, and the banded rectangles sub-divide the force plate surface into three zones, Perimeter, Mid Zone and Central Zone. There was a missing data set at point (160, -160) which is shown as a solid grey ellipse in Figure 4.11. The size of this ellipse was calculated from the mean of the three corresponding locations (160,160), (-160,160) and (-160,-160). For comparison with the static tests the corner and mid line points have been included in Table 4.2.

Table 4.2. RMS errors in force plate dynamic point of force application (mm).

<table>
<thead>
<tr>
<th>RMS errors (mm)</th>
<th>N</th>
<th>Mean</th>
<th>St.Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corners</td>
<td>4</td>
<td>13.1</td>
<td>±2.9</td>
</tr>
<tr>
<td>Mid line</td>
<td>4</td>
<td>10.4</td>
<td>±4.2</td>
</tr>
<tr>
<td>Perimeter</td>
<td>19*</td>
<td>12.0</td>
<td>±4.0</td>
</tr>
<tr>
<td>Central Zone</td>
<td>3</td>
<td>4.1</td>
<td>±2.9</td>
</tr>
<tr>
<td>Mid Zone</td>
<td>12</td>
<td>6.4</td>
<td>±4.1</td>
</tr>
</tbody>
</table>

(See Figure 4.8 for definition of Perimeter, Mid Zone and Central Zone)
The common points (corners and mid line) show that under the dynamic loading conditions the RMS errors were at least 50% greater than those observed for the static loading conditions. The perimeter values were similar in size to the corner values, but that within the mid zone the errors were approximately half those seen near the edges of the plate. The central zone had the smallest mean errors at 4.1 mm.

The standard deviation values obtained in the dynamic test were approximately ten times larger than those seen for the static test. It would therefore appear that the accuracy of point of force application data recorded near the centre of the plate, whether dynamically or statically loaded, is consistently superior to that recorded near the edges of the plate. This is in general agreement with Bobbert and Schamhardt (1990) study although the errors appear to be larger in the current study, albeit for a different sized plate mounted on a different frame.

**Force data sampling**

The resonance of the new mounting and plate combination was in excess of 500 Hz. It was therefore suitable for the data capture necessary for the jumping study providing that appropriate sampling and filtering were employed to ensure that this resonance did not alias into the data field. A sampling frequency of less than 1 kHz was unacceptable due to the Nyquist sampling theorem limit which states that the sampling rate must be at least twice that of the maximum frequency of interest. Although the resonance was not of interest in its own right the potential for contaminating the real movement data generated during the planned rebound jumping action meant that the input signal had to be band limited. An ideal solution would have been to use an analog anti-aliasing filter with a cut-off frequency below that of the plate's minimum resonance. A suitable hardware solution was not available at the time and so a software solution had to be adopted. Within the machine coded routines provided with the laboratory interface (CED1401) was a bi-linear filter with a sharp cut-off and Butterworth style frequency profile. The sampling frequency to cut-off frequency ratio of the selected software filter was 10.24 and thus to maintain all frequencies up to 500 Hz, a sampling frequency in excess of 5 kHz per channel was required. Previous frequency analyses of human impact studies in running and hurdling by Kerwin and Chapman (1988) had shown that peak frequency components of 125 Hz in the vertical force component were possible during the most acute hurdle landings. Very high frequency components in excess of 600 Hz had been recorded but subsequent analysis revealed that the signal energy in these lateral force components were insignificant. Takeoff frequency peaks were generally lower than 50 Hz. Frequency components up to 125 Hz were required, whereas those in excess of 500 Hz were unwanted. To meet the Nyquist limit a cut-off frequency of around 250 Hz was ideal. Bearing in mind that the software solution prescribed a sampling to cut-off frequency ratio of 10.24, a sampling frequency of 2.5 kHz was selected. This meant that the effective cut-off frequency would be at 244 Hz.
A final consideration remained to be considered. If frequency components in the plate and its new mounting in excess of the tested range of up to 2 kHz existed, these could alias into the new band limited signal without detection. Using the Nyquist Theorem, the modal analysis procedure needed to be extended to the 5 Hz range to obviate this problem. An independent modal analysis and an alternative vibration analysis derived from holography known as electronic speckle pattern interferometry (ESPI) were carried out in the Mechanical Engineering department at Loughborough University and reported by Lad (1988). All the results obtained in this separate study supported the findings of the current analysis and demonstrated that, even when the testing range was extended to 5 kHz, the highest frequency detected was 1935 Hz. Allowing for the folding effect at the Nyquist limit, this frequency could have appeared at the 685 Hz (1935-1250) and would thus be beyond the 500 Hz critical limit. It was therefore decided that sampling at 2.5 kHz was sufficient to provide the time resolution required without jeopardising the fidelity of the data due to force plate resonances or their aliases appearing in the recorded signal.

A sampling frequency of 2.5 kHz for multiple channels introduced data storage problems. The time required for the complete rebound jumping action was approximately five seconds and hence the volume of data which would be generated was greater than the standard internal RAM capacity of the laboratory interface and therefore a block of internal RAM was used. This was divided into 64 kbyte banks, numbered from 0 to 11. Each trial was allocated two banks totalling 128 kbytes. All analog data were converted to two 8 bit bytes of unsigned binary digital data, accurate to 12 bits. With the aggregate sampling frequency for four data channels at 2.5 kHz per channel and a capture period of 4.8 seconds a total of 2*4.8*10 kbytes per trial was required. The first 96 kbytes of the available 128 kbytes for each trial were used. When a trial was accepted a data pointer moved onto the next pair of data banks. If a trial was rejected the current pair of banks were re-used. At the completion of the six trials, data were automatically transferred into the CED1401 working array and separated from serial to parallel format using the CED1401 ‘SN2’ array processing command. These data were then transferred via the controlling computer onto 640 kbyte 3.5” floppy discs for later analysis. The computer program ‘MAREYjp’ (Appendix B4.1) was written to achieve this data capture, manipulation and storage. The 12 bit analog to digital converter (ADC) was operated in burst sampling mode. At maximum rate the ADC conversion time was 10 microseconds per sample. By running the ADC at maximum speed over the four channels, the signals were sampled within 30 microseconds of each other. The alternative method of serial sampling could have been used but the delay between samples would have been 100 microseconds. In this mode the fourth channel sample of the first epoch would have been closer in time to the first channel sample of the second epoch than to the first channel of its own epoch.

The accuracy of the ADC was specified as \( \frac{1}{2} \) the least significant bit for data sampled at the 12
bit level which meant that the force data were resolved into 4096 steps but were accurate to 1 part in 8192. The accuracy of the force plate reported earlier was considerably less than this and therefore the ADC was not a limiting factor in quantising the analog output from the force plate amplifiers.

**Triggering and data synchronisation**

To facilitate synchronisation of film and force plate data a shutter pulse was taken from an output socket on the high speed cine camera, fed via a stroboscopic unit which detected the analog waveform delivered by the shutter output and converted it into a needle pulse which was fed into one channel of the analog to digital converter. Vertical force ($F_z$), horizontal force ($F_y$) and point of force application ($a_y$) were sampled on three other channels.

Timing the start and finish of each jumping action was not critical since the action could be subdivided into precisely timed stages at a later stage. Triggering of the data capture period was accomplished via a manually controlled push button contact closure detected via the Event 4 connector on the interface. This input was linked internally to the analog to digital converter circuitry.

**4:3.4 DISCUSSION**

Problems associated with mounting the force plate in the laboratory arose because the ideal concrete grouted solution was not possible. Bolting the standard mounting frame to the floor of the laboratory resulted in poor alignment of the planar surfaces of the four main pillars. The effect on the force plate and mounting, of this variable alignment, was detected using modal analysis and highlighted natural frequencies of vibration much lower than the manufacturer's design specifications with values below 400 Hz. During tests, before the spacers under the cross members had been installed, the lowest natural frequency recorded was below 300 Hz. These results highlighted problems, since resonances in the force plate and its mounting could alias into the recorded signal during dynamic human movements like the rebound jumping activities which were to follow. These frequencies would be undetectable under normal recording conditions but could influence the force data used in the subsequent analyses. An alternative force plate mounting in an outdoor location, which had been designed to meet the manufacturer's specifications, was subjected to modal analysis. The expected frequency responses from the force plate and its mounting were obtained indicating that the lowest natural frequency of the plate when on an ideal mounting was in excess of 750 Hz. An alternative mounting frame was designed which was more appropriate for surface mounting in the laboratory. It was necessary to provide a stable and consistent base for the plate which would produce frequency response characteristics closer to those achievable when using the ideal grouted mounting. Although the high specifications obtainable in the ideal location were not
achieved, a minimum natural frequency for a newly constructed solid mounting frame and force plate above 500 Hz was obtained consistently. It was therefore possible to be confident that no frequencies below 500 Hz were present in the recorded signal irrespective of the jumping action performed on the plate. Ideally an analog anti-aliasing filter with a cut-off frequency at around 500 Hz could have been fitted to the ADC to prevent the identified fundamental frequency, its associated harmonics or any other frequency components from other modes of vibration and their harmonics from entering the recorded data. This was not an option at the time that the experimental data was recorded as a suitable analog unit did not exist. An alternative software solution was adopted. The sampling frequency to cut-off frequency ratio of the selected software filter was 10.24 and thus to maintain all frequencies up to 500 Hz, a sampling frequency in excess of 5 kHz per channel was required. Previous frequency analyses of human impact studies in running and hurdling by Kerwin and Chapman (1988) had shown that peak frequency components of 125 Hz in the vertical force component were possible during the most acute hurdle landings. Very high frequency components in excess of 600 Hz had been recorded but subsequent analysis revealed that the signal energy in these lateral force components were insignificant. Takeoff frequency peaks were generally lower than 50 Hz. Frequency components up to 125 Hz were required, whereas those in excess of 500 Hz were unwanted. To meet the Nyquist limit a cut-off frequency of around 250 Hz was ideal to meet this criterion. Bearing in mind that the software solution prescribed a sampling to cut-off frequency ratio of 10.24, a sampling frequency of 2.5 kHz was selected. This meant that the effective cut-off frequency would be at 244 Hz. A final consideration remained. If frequency components in the plate and its new mounting in excess of the tested range of up to 2 kHz existed, these could alias into the new band limited signal without detection. Using the Nyquist Theorem, the frequency analysis procedure was extended to the 5 Hz range to obviate this problem. An independent modal analysis and an alternative vibration analysis derived from holography known as electronic speckle pattern interferometry (ESPI) were carried out in the Mechanical Engineering department at Loughborough University and reported by Lad (1988). All the results obtained in this separate study supported the findings of the current analysis and demonstrated that, even when the testing range was extended to 5 kHz, the highest frequency detected was 1935 Hz. Based on the findings of the modal analyses, the newly designed solid mounting frame and force plate combination was used for all the subsequent jumping experiments.

Calibration tests were undertaken to ensure that the accuracy of the force plate had not been compromised by changes to its mounting. Static and dynamic loading tests were conducted to check magnitude of force and point of force application on the surface of the plate. The static tests indicated that the expected accuracy of <1% for vertical forces was easily achieved and that for static tests the errors were close to 0.1%. In the dynamic tests the expected ±2 mm errors in point of force application were only achievable within the central region of the plate.
This occurred in about 30% of the total points tested. In the worst cases, root mean square errors as large as 13 mm had been recorded at the corners of the plate. Static point of force loading errors were in general about half the size of those observed during the dynamic tests. As the primary concern was the performance of the plate on its new mounting, tests in situ only were considered. Calibration of the plate alone had previously confirmed that the claimed accuracy of <1% for vertical forces and <2% for horizontal forces were comfortably achieved. Vertical force calibration only had been checked by loading the plate with calibrated weights. Inevitably some components of force from the horizontal transducers were involved in the determination of the point of force data, but these outputs were not independently checked. A recent paper by Hall et al., (1996) reported a series of procedures for calibrating a force plate in situ and included details of powerful statistical analyses to evaluate the data. They also highlighted cross-sensitivity errors which had not been considered in the current calibration procedures. All errors were smaller in static loading than dynamic loading conditions and even in the latter cases, the magnitudes of force errors were smaller than expected. The point of force application errors, providing only the central zone of the plate was considered, were also small. These errors may have influenced the kinetic analyses of rebound jumping and so a sensitivity analysis was undertaken to investigate the influence of small variations in the location of ground reaction force vectors on an inverse dynamic analysis of jumping mechanics.

Specification of the force data capturing procedures for the proposed study of rebound jumping had been completed, but to enable inverse dynamics to be undertaken, visual information describing limb movements was also required. To match the sampling rate specified in the force analysis, a relatively high framing rate was desirable. High speed cinefilm and video were the options available. Cinefilm is a proven format, used extensively in biomechanics research, but limited because the image to be recorded is not visible at the time of data collection and can only be confirmed as suitable once the film has been processed. Video by contrast offers immediate viewing of the final image at the time of recording and therefore a guarantee of a successful data recording session. The accuracy of 16 mm cinefilm is well established in biomechanical analyses but video is less commonly used and the resolution of video images varies from one format to another. To obtain a relatively high framing rate a non standard video camera and recorder combination were required. An NAC 200 Hz video system was available, but accuracy figures on the data obtainable from this NTSC format used by this camera and recorder combination were not available. It was possible to convert the recorded data onto standard PAL video tape (VHS or U-Matic) running at 50 Hz and so a series of calibration experiments were designed to compare the resolution and accuracy of video and cinefilm based recording and digitising systems. Synchronisation in time had been achieved by the use of a shutter pulse output recorded simultaneously with the force plate data. Synchronisation in space was necessary. The centre of the force plate is the origin for the point of force application data and so using this as the visual image origin made spatial synchronisation direct and simple.
However, aligning the appropriate video or cinefilm camera with the centre of the field of view was not immediately achievable. The optical axis of a camera lens and the geometric centre of the lens are not necessarily coincident and cannot readily be aligned with a fixed point in the centre of the field of view. Therefore image offsetting and rotation together with scaling were necessary before the visual and force data could be combined. The next section contains the details of the experiments carried out to evaluate these imaging requirements.
4:3 CINE-FILM AND VIDEO TAPE RECORDING AND DIGITISATION

4:3.1 INTRODUCTION

The following experiment examined the spatial resolution and measurement accuracy of cine-film and video tape with their associated digitisation procedures. The two systems were compared using different combinations of lenses, recorded image sizes and digitised image sizes. Two primary formats for image recording were compared; 16 mm cine-film and super 'VHS' (sVHS) video tape. The cine-film system comprised a cine-camera (Bolex EB16x), an analysis projector (NAC Motion Analyser) and a digitising tablet (TDS HR48). Two lenses were evaluated; a 16 mm fixed focal length lens and a zoom lens (Schneider Krenznach, f1.8 10-100 mm cine zoom). The video system comprised a charge coupled device (CCD) video camera (Panasonic F15) fitted with a zoom lens (Panasonic f1.2 10-150 mm video zoom), an sVHS video recorder (Panasonic AG7350) and a video digitising frame store (Video Electronics Limited, Arvis sVHS graphics card with PAL encoder and genlock) fitted inside a computer (Acorn Archimedes A410/4).

4:3.2 METHOD

**Calibration Grid and Markers**

A calibration grid was prepared on a large scale high resolution digitising tablet (Terminal Display Systems HR48). Five rows of seven circular markers of diameter 0.03 m (Figure 4.12a) were located horizontally and vertically at approximately 0.195 m intervals, (Figure 4.12b). The marker design was selected following experimentation with plain black and white circles and circles with alternately marked quadrants. In addition diagonal, and horizontal and vertical crosses, together with combinations of circles and crosses were tested. The target shape which provided the clearest image was selected. The 35 markers were digitised ten times consecutively by two independent and experienced operators. From these data a combined criterion data set of 35 data pairs was obtained \((c_{x_i}, c_{y_j})\). The criterion data are listed in Appendix 4.3. These were used to evaluate the root mean square difference (RMSD) values for each of the image recording and analysis systems.

**Data Recording and Digitisation**

Cine-film recordings were made with two different lenses. A fixed focal length 'C' mount lens provided an image of approximately 2 m in width. A 'C' mount zoom lens was then fitted and adjusted until the calibration grid filled the image. The film digitising program !CineDig was used to collect the data. This program has been listed in Appendix B5.1.
Figure 4.12a. Criterion marker of diameter 3 cm showing concentric circles and intersecting pointed arrow heads.

Figure 4.12b. Marker layout showing distribution of 35 markers in 5 rows of 7 columns.
When the video camera was used, the camera’s zoom lens was adjusted until the image matched the width of the image obtained with the fixed focal length cine lens. Later the lens was zoomed in to fill the image with the width of the calibration grid. Since the aspect ratios of cine and video are not the same the total image height for the two formats were different. At the digitising stage, the film image was projected from a constant distance (2.48 m) with a fixed focal length lens (25 mm) onto the tablet digitiser producing images of the calibration grid which were of 1.17 m and 0.84 m in width respectively for the fixed and zoomed lens recordings. For video digitising the images were presented at normal size, that is with the image filling the video screen within a frame store of resolution of 256 pixels vertically and 640 pixels horizontally. This image could be doubled in both directions giving an effective resolution of 512 x 1280 pixels by selecting the zoom option. In all cases ten consecutive images were digitised. The video images were digitised using the ‘Biomechanics Workstation’ software package and the resulting output files were converted into a common format for comparison with the criterion and film derived files.

**Calculation of image origin, scaling and rotation parameters**

Mean values \( (c_{x0}, c_{y0} \text{ and } x_0, y_0) \) for each data set were calculated from equations 4.5i-iv and used as origin coordinates for the criterion and each of the digitised data sets respectively.

\[
x_0 = \frac{\Sigma x_i}{n}, \quad y_0 = \frac{\Sigma y_j}{n}, \quad c_{x0} = \frac{\Sigma c_{x0}}{n}, \quad c_{y0} = \frac{\Sigma c_{y0}}{n}
\]

4.5 (i, ii, iii, iv)

Where there are \( i \) columns and \( j \) rows, giving \( n = i \times j \), in this example \( i = 7, j = 5 \), \( n = 35 \)

Scale factors \( s_x \) and \( s_y \) were determined using equation 4.6 such that the sum of squared differences \( (D_x \text{ and } D_y) \) between the scaled image data set \( (s_x x_i, s_y y_j) \) and the criterion data set \( (c_{x0}, c_{y0}) \) was at a minimum. Equation 4.6 scaled the data horizontally and a similar equation in \( y \) was used for scaling vertically.

\[
D_x = \sum_i^n (s_x x_i - c_{x0})^2
\]

4.6

Differentiating equation 4.6 to determine \( \delta D/\delta s \) produced equation 4.7.

\[
\frac{\delta D_x}{\delta s_x} = \sum_i^n 2(s_x x_i - c_{x0}) x_i = 2 \left[ s_x \sum_i^n x_i^2 - \sum_i^n c_{x0} x_i \right]
\]

4.7

\( D_x \) will be a minimum when \( \delta D_x/\delta s_x = 0 \), that is when:
Similarly a scaling value \( s_y \) was calculated from equation 4.8 in \( y \) to provide scaling for the vertical coordinate data. These two \( s \) values (\( s_x \) and \( s_y \)) were approximately equal. The fit over the 35 points was then evaluated by determining the mean square difference (MSD) over the ten digitised sets of the 35 \((x, y)\) pairs using equation 4.9.

\[
\sigma_x^2 = \frac{\sum_{i,j,k} (s_x x_{ijk} - cx_{ijk})^2}{\sum_{i,j,k}}
\]

Where \( i = \) columns, \( j = \) rows and \( k = \) digitisations. \((i = 1 \text{ to } 7, j = 1 \text{ to } 5 \text{ and } k = 1 \text{ to } 10)\)

A similar mean square deviation value for \( y \) \((\sigma_y^2)\) was calculated using a 'y' version of equation 4.9. A new data set \((x_i', y_i)\) was then formed by scaling the input data \((x_i, y_i)\) such that

\[
x_i' = s_x x_i \text{ and } y_i' = s_y y_i
\]

The data were also translated to a common origin.

At the data recording and projection stages, care had been taken to ensure that the centre of the lens was central to the field of view and that the camera was level and horizontal. That is camera pan and tilt were accounted for but camera "roll" or screw about the viewing axis was more difficult to reduce to zero. A software approach was therefore taken. An angle \( \theta \) through which to rotate the scaled and offset coordinates was then determined. The aim was to find the value of \( \theta \) such that the rotated digitised data set most closely matched the criterion data set. The input points \((x_i', y_i')\) were mapped to the rotated points \((x_i'', y_i'')\) using the two dimensional rotation matrix shown in (4.10).

\[
\begin{bmatrix}
\cos \theta, & -\sin \theta \\
\sin \theta, & \cos \theta
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix}
= 
\begin{bmatrix}
x \cos \theta - y \sin \theta \\
x \sin \theta + y \cos \theta
\end{bmatrix}
\]

Minimising the mean square deviation between the new data set \((x_i'', y_i'')\) and the criterion data set \((cx_i, cy_i)\) was achieved by minimising \( D_r \), where:
\[ D_r = \sum [(x. \cos \theta - y. \sin \theta - cx)^2 + (x. \sin \theta + y. \cos \theta - cy)^2] \]  
4.11

\[ \delta D_r/\delta \theta = \Sigma [2(x. \cos \theta - y. \sin \theta - cx) \cdot (-x. \sin \theta - y. \cos \theta) + 2(x. \sin \theta + y. \cos \theta - cy) \cdot (x. \cos \theta - y. \sin \theta)] \]  
4.12

For a minimum value of \( D_r \), \( \delta D_r/\delta \theta = 0 \), that is:

\[ \tan \theta = \Sigma (cy.x - cx.y)/\Sigma (cx.x + cy.y) \]  
4.13

Substituting \( \theta \) into equation 4.11 enabled the root mean square deviation between this final data set \((x_i^*, y_i^*)\) and the criterion data set \((c_{x_i}, cy_j)\) to be determined. The residuals were calculated prior to and following the rotation by \( \theta \) and plotted to investigate the distribution of the distortion still remaining in the image data, (Figure 4.13c).

**Maximum Points Tests**

In addition to the RMSD scores calculated using equations 4.6 and 4.11, another series of tests was conducted based on the data from the full calibration grid of 35 points. Effective resolution in horizontal \((x)\) and vertical \((y)\) coordinates of each system was calculated from the average of the individual point standard deviations for the 35 calibration grid points, for the ten separate digitisations, divided by the image size measured in the same units. This was repeated for the criterion data set and for each of the of digitised image data sets. A resolution performance as the square root of the sum of squares of the \(x\) and \(y\) values was then calculated for each image recording and digitising combination. These were then averaged across the different image recording and digitising sizes for film and video to produce a set of overall resolution performance scores \((P_\gamma)\).

**Minimum Points Tests**

A series of tests were conducted in which subsets of the criterion and image digitised input data were used to perform the same calibration calculations described for the 35 point array. The aim was to determine a minimum number of reference points, and the locations within the image for these reference points which would produce essentially the same offset, scaling and rotation factors as the full 35 point array. Four sub-sets of criterion and input data were selected ranging from 4 points to 15 points, see Table 4.3. Figure 4.12c shows the four sub-sets, ranging from 15 central zone points (CZP), through 9 distributed points (D9), 9 central points (C9) and finally 4
extreme corner points (ECP). In each case the origin ('centre' of the data set), the scaling factors in x and y and the rotation angle $\theta$ were calculated from the input data set.

Figure 4.12c. Four sub-sets of calibration points.
Figure 4.12d. Calibration points, 20 open circles, and independent check points, 15 grey filled circles.
Table 4.3. Sub-sets of criterion and digitised data used for calibration.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Points</th>
<th>Criterion/Input Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (CZP)</td>
<td>15</td>
<td>Rows 2,3 &amp; 4 and columns 2 - 6</td>
</tr>
<tr>
<td>2 (D9)</td>
<td>9</td>
<td>Rows 1, 3 &amp; 5, points 1, 4 &amp; 7</td>
</tr>
<tr>
<td>3 (C9)</td>
<td>9</td>
<td>Rows 2, 3 &amp; 4, points 2, 4 &amp; 6</td>
</tr>
<tr>
<td>4 (ECP)</td>
<td>4</td>
<td>Rows 2 &amp; 4, points 2 &amp; 6</td>
</tr>
</tbody>
</table>

The digitised data were then offset, scaled and rotated before being compared with the criterion data set under six different conditions, see table 4.4. A standard (RMSD) against which all the RMSD values could be compared was regarded as the RMSD value obtained when using the 16 mm cine-film with the fixed focal length lens and all 35 data points. By dividing the RMSD score for each system by the standard RMSD, a single dimensionless value was obtained which could be used for comparison across different camera, lens, digitiser and calibration point combinations.

Table 4.4. RMSD comparison conditions using sub-sets of criterion & digitised data sets.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Condition</th>
<th>Comparison Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>All Data</td>
</tr>
<tr>
<td>2</td>
<td>R35</td>
<td>All Data after Rotation</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>Central Data</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>Half Image Data</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>Adjusted Half Image Data</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Independent Central Data</td>
</tr>
</tbody>
</table>

Imaging Accuracy Tests

Imaging accuracy was determined using 20 of the 35 points in the calibration grid array for offset, scaling and rotation purposes and then using the remaining 15 points (Figure 4.12d) independent points as the criterion against which to check the accuracy with which each system could predict the locations of these known points.

4:3.3 RESULTS

Image rotation analysis

The film data needed to be rotated through a larger angle and in the opposite direction to the video image data, (Table 4.5). As the film data is a result of both camera and projector "roll" and the video data is a result only of camera roll it is not surprising that the values are different. The fact that the two systems required rotation in opposite directions is also not important, but is
an indication that setting up film or video cameras to be perfectly horizontal about two axes is not readily achievable. In all cases rotating the image improved the quality of the fit between the digitised data and the criterion data.

Table 4.5. Root mean square differences using 35 point calibration array pre rotation and post rotation by angle $\theta^\circ$.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSD (mm)</th>
<th>$\theta$ (°)</th>
<th>RMSD(R) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Details</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion</td>
<td>0.14</td>
<td>0.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Film (16)</td>
<td>5.12</td>
<td>-0.52</td>
<td>2.67</td>
</tr>
<tr>
<td>Film (Zoom)</td>
<td>6.31</td>
<td>-0.68</td>
<td>2.84</td>
</tr>
<tr>
<td>Video(Match)</td>
<td>4.72</td>
<td>0.33</td>
<td>3.82</td>
</tr>
<tr>
<td>Video(Zoom)</td>
<td>6.69</td>
<td>0.43</td>
<td>5.67</td>
</tr>
</tbody>
</table>

RMSD = root mean square difference between digitised and criterion data, (R) = following rotation by angle $\theta^\circ$. The Film (16) data were obtained using a 16 mm fixed focal length lens, the Video(Match) data were obtained with a zoom lens adjusted to match the video image to the film image (allowing for the different aspect ratios of the the two recording formats). (Zoom) appended to Film and Video indicates the data obtained when the respective zoom lenses had been adjusted to maximise the image size of the control object, 1.170 m x 0.780 m.

Maximum Points Tests

The RMSD scores for the criterion and digitised image data pre and post rotation have been reproduced in Table 4.6, with additional values added. The third column contains the dimensionless value $D/D_s$ which is a ratio of the RMSD score for the system under study in relation to the standard value RMSD$_s$ obtained using the 16 mm cine-film and fixed focal length lens combination. The final column contains a value R+. This is the percentage improvement $(100*{(D-D_R)/D_R})$ in the RMSD score as a result of performing the rotation through $\theta^\circ$ based on equation 5.9. The 0% improvement for the criterion data set is expected.

Table 4.6. RMSD scores from 35 point calibration array pre rotation, RMSD, and post rotation, RMSD(R), for criterion and digitised data.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSD (mm)</th>
<th>RMSD(R) (mm)</th>
<th>$D/D_s$ (%)</th>
<th>R+ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Details</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.14</td>
<td>0.14</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>F(16)</td>
<td>5.12</td>
<td>2.67</td>
<td>1.00</td>
<td>92</td>
</tr>
<tr>
<td>F(Z)</td>
<td>6.31</td>
<td>2.84</td>
<td>1.06</td>
<td>122</td>
</tr>
<tr>
<td>V(M)</td>
<td>4.72</td>
<td>3.82</td>
<td>1.43</td>
<td>24</td>
</tr>
<tr>
<td>V(Z)</td>
<td>6.69</td>
<td>5.67</td>
<td>2.12</td>
<td>18</td>
</tr>
</tbody>
</table>

$D/D_s$ = the dimensionless ratio of RMSD with reference to RMSD$_s$. R+ = Percentage improvement in the RMSD value as a result of rotating the image coordinates. C = Criterion, F = Film data, V = Video data, (16) = 16 mm fixed focal length lens, F(Z) = zoom lens, V(Z) = zoomed image, (M) = zoom lens altered to match fixed focal length lens.

The higher the percentage improvement, the greater the angle through which the image had to be rotated and therefore the greater must have been the camera-projector misalignment. The results for the effective resolution of each system and the overall resolution performance ($P_1$) are shown in Table 4.7. Although the standard deviation values for film and video are not
dramatically different the units of measurement are not the same. The video system was limited to integer pixel steps and so the effective resolution of the video system was only about \( \frac{1}{4} \) of that available using the cine-film based system.

Table 4.7. Effective resolution of film and video based recording and digitising systems.

<table>
<thead>
<tr>
<th>System</th>
<th>SD_x</th>
<th>SD_y</th>
<th>RNG_x</th>
<th>RNG_y</th>
<th>RP_x</th>
<th>RP_y</th>
<th>RP_xy</th>
<th>P_r</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>F(16)</td>
<td>1.30</td>
<td>0.64</td>
<td>1560</td>
<td>1050</td>
<td>1200</td>
<td>1636</td>
<td>2029</td>
<td>2082</td>
<td>mm</td>
</tr>
<tr>
<td>F(Z)</td>
<td>1.00</td>
<td>0.45</td>
<td>1560</td>
<td>1050</td>
<td>1197</td>
<td>1769</td>
<td>2136</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>V(M)</td>
<td>1.04</td>
<td>2.32</td>
<td>640</td>
<td>256</td>
<td>615</td>
<td>110</td>
<td>625</td>
<td>556</td>
<td>pixel</td>
</tr>
<tr>
<td>V(Z)</td>
<td>3.01</td>
<td>2.16</td>
<td>1280</td>
<td>512</td>
<td>425</td>
<td>237</td>
<td>486</td>
<td></td>
<td>pixel</td>
</tr>
</tbody>
</table>

SD = Standard Deviation, RNG = Range of possible values from digitiser, RP = resolution performance as a ratio (RNG/SD), P_{xy} = Resolution Performance for x and y combined and P_r = Overall performance of the system based on the average of each appropriate RP_{xy}. NB. P_r for the criterion score is approximately 60,000.

**Minimum Points Tests**

Each sub-set of points was used in turn to obtain root mean square difference scores which were compared with the previously obtained data obtained using the full 35 point data set. The results are presented in Table 4.8. The average root mean square difference values obtained with film images are always smaller than those obtained with video irrespective of the sub-set of points used to generate the offset, scaling and rotation factors. When using cine-film images obtained using a fixed focal length lens the value of D_y ranged from 3.30 mm to 2.15 mm with both the standard deviation and the mean values being 2.67 mm. When using the zoom lens with the 16 mm camera, using points around the edge of the image to generate the required scaling factors an RMSD value was obtained which was similar to that obtained using all 35 points. A value of half this magnitude was obtained when points more central to the image were used. This would indicate that the zoom lens used introduced some distortion which was particularly noticeable near the edges of the image. "Zooming in" to fill the image with the subject therefore resulted in larger overall errors and less uniform scaling across the field of view. Keeping the subject near to the central zone of the field of view was clearly advantageous to accuracy and avoided the need to employ lens correction algorithms. With the data obtained from video recordings, whether the central part of the lens (VM) or the whole of the lens (VZ) was used the resulting RMSD values were always in excess of 3 mm, averaged 3.6 mm for the matched image and were about 50% larger for the zoomed image. The data for all the other tests also indicated that the cine-film derived values were consistently more reliable than those obtained with video.

The effects of digitising data points at the extremes of the field of view are less noticeable with cine-film than with video. However, using the 9 central points with the fixed focal length lens/cine-film system produced offset, scaling and rotation data which when compared with the known locations of the six central check points (points which were within the calibrated range.
but which had not been included in the calibration calculations) resulted in root mean square difference value of 2.1 mm. Using the four extreme corner data points resulted in a root mean square difference for the same six central check points of 3.4 mm. If these figures are compared with the video system the corresponding root mean square difference values are 4.7 mm and 5.3 mm. When all the combinations of input data points and criterion data points for the six central check points were combined the root mean square difference for the cine-film system was 2.5 mm. The corresponding video system was twice as large at 5.0 mm. Using zoom lenses on the cine-film and video camera facilitated making the image of the calibration grid fill the field of view. As a result any weaknesses in the lenses, which are more common in the peripheral rather than the central areas of the lens, would influence the linearity of the data. Thus, although the marker size and image clarity was enhanced by zooming the image, the use of the edges of the lenses for measurement reduced the overall quality of the data. The corresponding root mean square difference values for the six check point test were 3.7 mm and 7.0 mm for the cine-film and video systems respectively. Once again a factor of two exists between the two systems.

Table 4.8. RMSD (mm) data sub-set comparisons between the number of points and image location with respect to the full 35 point data array.

<table>
<thead>
<tr>
<th>Sub-Set</th>
<th>Points</th>
<th>D,</th>
<th>ALL</th>
<th>CZP</th>
<th>HID</th>
<th>AHID</th>
<th>ICD</th>
</tr>
</thead>
<tbody>
<tr>
<td>F(16)</td>
<td>35</td>
<td>2.67</td>
<td>2.67</td>
<td>2.33</td>
<td>2.45</td>
<td>2.94</td>
<td>2.25</td>
</tr>
<tr>
<td>CZP</td>
<td>15</td>
<td>2.15</td>
<td>2.86</td>
<td>2.15</td>
<td>2.64</td>
<td>3.16</td>
<td>2.05</td>
</tr>
<tr>
<td>D9</td>
<td>9</td>
<td>3.03</td>
<td>2.81</td>
<td>2.67</td>
<td>2.57</td>
<td>3.09</td>
<td>2.63</td>
</tr>
<tr>
<td>C9</td>
<td>-9</td>
<td>2.21</td>
<td>2.84</td>
<td>2.17</td>
<td>2.58</td>
<td>3.09</td>
<td>2.10</td>
</tr>
<tr>
<td>ECP</td>
<td>4</td>
<td>3.30</td>
<td>3.29</td>
<td>3.36</td>
<td>3.07</td>
<td>3.68</td>
<td>3.36</td>
</tr>
<tr>
<td>Mean</td>
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<td>2.89</td>
<td>2.54</td>
<td>2.66</td>
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<td>2.48</td>
</tr>
<tr>
<td>F(Z)</td>
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<td>2.84</td>
<td>2.84</td>
<td>2.35</td>
<td>2.38</td>
<td>2.48</td>
<td>2.98</td>
</tr>
<tr>
<td>CZP</td>
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<td>1.49</td>
<td>3.41</td>
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<td>3.32</td>
</tr>
<tr>
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<td>1.61</td>
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<td>1.61</td>
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<td>4.12</td>
<td>3.45</td>
<td>4.15</td>
</tr>
<tr>
<td>Mean</td>
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<td>2.54</td>
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<td>3.67</td>
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<tr>
<td>V(M)</td>
<td>35</td>
<td>3.82</td>
<td>3.82</td>
<td>4.01</td>
<td>3.77</td>
<td>3.90</td>
<td>4.68</td>
</tr>
<tr>
<td>CZP</td>
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<td>3.81</td>
<td>4.14</td>
<td>3.81</td>
<td>3.61</td>
<td>4.01</td>
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<td>4.57</td>
<td>4.25</td>
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</tr>
<tr>
<td>C9</td>
<td>-9</td>
<td>3.94</td>
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<td>3.82</td>
<td>3.64</td>
<td>3.95</td>
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<td>4.16</td>
<td>3.91</td>
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<td>4.98</td>
</tr>
<tr>
<td>V(Z)</td>
<td>35</td>
<td>5.67</td>
<td>5.67</td>
<td>5.65</td>
<td>5.94</td>
<td>5.77</td>
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</tr>
<tr>
<td>CZP</td>
<td>15</td>
<td>5.53</td>
<td>5.85</td>
<td>5.53</td>
<td>5.72</td>
<td>5.87</td>
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</tr>
<tr>
<td>D9</td>
<td>9</td>
<td>5.83</td>
<td>5.74</td>
<td>5.78</td>
<td>6.09</td>
<td>5.84</td>
<td>7.01</td>
</tr>
<tr>
<td>C9</td>
<td>-9</td>
<td>5.39</td>
<td>5.75</td>
<td>5.55</td>
<td>5.78</td>
<td>5.80</td>
<td>6.96</td>
</tr>
<tr>
<td>ECP</td>
<td>4</td>
<td>5.90</td>
<td>5.86</td>
<td>5.96</td>
<td>6.30</td>
<td>5.93</td>
<td>7.11</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>5.66</td>
<td>5.77</td>
<td>5.69</td>
<td>5.97</td>
<td>5.84</td>
<td>7.01</td>
</tr>
</tbody>
</table>

Sub-Set: CZP = Central Zone Points group, D9 = Distributed 9 point group, C9 = Central 9 point group, ECP = Extreme Corner Points. D, = RMSD calculated from sub-sets of input and criterion data and used to estimate offset, scaling and rotation factors. (NB when points= 35 D, = RMSD), ALL = 35 Points, HID = Half Image Data, AHID = Adjusted Half Image Data, ICD = Independent Central Data.
Figure 4.13a. Root Mean Square Differences as a measure of reliability for digitising film and video images using lenses of fixed and variable focal lengths.

Figure 4.13b. Full Accuracy Test based on Root Mean Square Differences for 15 check points with offset, scaling and rotation based on 20 control points distributed throughout the field of view.
Figure 4.13c. Reduction in cinefilm digitisation errors using rotation correction for Film (Zoom) data. Correction for camera "roll" between images (i) and (ii).

The influence of camera "roll" on image RMS errors is shown diagrammatically with the criterion points appearing as solid circles and the arrows pointing in the direction of each digitised point. The magnified vectors have been scaled by a common factor in both images to illustrate the errors.
Data from the central portion of the image (HID Table 4.8), was then used to assess the overall root mean square difference values for a horizontal band of 12 data points evenly distributed across the full width but only occupying the central half of the image height. The root mean square difference values for the cine-film/fixed focal length system was 2.6 mm, and for the video system 3.6 mm. When the zoomed images were studied the corresponding values were 1.5 mm and 5.7 mm respectively. An adjusted set (AHID Table 4.8) provided a better indication of the likely variability that could be expected. The adjustment was made on the basis that two of the points in this calibration array were also present in the checking array. The root mean square difference values were therefore scaled accordingly. The results therefore were not changed in ratio only in magnitude with the most likely size of the root mean square difference value being between the HID and AHIS values reported. A summary graph is shown in Figure 4.13a. The four groups of data show that with a fixed focal length lens fitted film data can be scaled with all or a subset of points equally effectively.

Cine-film and zoom lens accuracy reduces if the extremes of the image have been used in the calibration process, but improved accuracy can be obtained if calibration and measurement are concentrated in the middle zone of the image. With video measurement the variability is higher than with cine-film, whatever set of control points are used.

**Imaging Accuracy Tests**

Some indication of accuracy could be determined using the RMSD values from the ICD column in table 4.8. These values were obtained using six points near the middle of the image that had not been included in the calibration process. The values from the video system were between 4.5 and 7.0 mm. The corresponding values for the film system were between 2.5 and 3.7 mm. When the full accuracy test based on 20 alternate points spread throughout the image were used for the calibration and the intervening 15 points (Figure 4.12d) were then used to check accuracy the data presented in Table 4.9 and in Figure 4.13b were obtained.

**Table 4.9. Accuracy test of film and video digitised data based on 20 point calibration and 15 point accuracy check using Root Mean Square Differences (mm).**

<table>
<thead>
<tr>
<th>System</th>
<th>D(R20)</th>
<th>D(15)</th>
<th>D(MJ)</th>
<th>Mean(System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F(16)</td>
<td>2.77</td>
<td>2.60</td>
<td>2.34</td>
<td>2.4</td>
</tr>
<tr>
<td>F(Z)</td>
<td>3.02</td>
<td>2.74</td>
<td>3.61</td>
<td></td>
</tr>
<tr>
<td>V(M)</td>
<td>3.70</td>
<td>4.01</td>
<td>2.47</td>
<td>5.9</td>
</tr>
<tr>
<td>V(Z)</td>
<td>5.81</td>
<td>5.52</td>
<td>8.28</td>
<td></td>
</tr>
</tbody>
</table>

F = Film, V = Video, 16 = fixed focal length lens (16 mm), M = Image Matched to fixed lens size, Z = Zoom, D = root mean square difference in mm, R20 = after rotation of image data and based on the 20 input points, (15) = using 15 control points at recorded image size, (MJ) = scaled to be equivalent to the proposed experimental field of view.
The fact that the RMSD values based on 15 independent points was in general smaller than the value obtained re-using the same 20 points included in the calibration process is interesting and unexpected. However, the differences are small and could probably be accounted for by the fact that the 20 point data set included the extreme left and right columns of data which were likely to be more affected by any lens distortion than those points used in the check point calculations. The accuracy with which a point could be located using cine-film was better than was possible with video by a factor of 2.5. Bearing in mind that these RMSD values are averaged over the field of view it would be reasonable to expect that 95% of points could be located to an accuracy of 1.96 x RMSD giving an accuracy of ±4.7 mm for film and ±11.7 mm for video.

4.4.4 DISCUSSION

The digitising tablet used in this part of the study as the control object enabled the criterion points to be located to a very high degree of accuracy. Variability in digitising the well defined target points was very small and less than 0.1 mm in both x and y directions and so was not a limiting factor. The tablet digitiser has a resolution of 0.025 mm but the standard deviation when digitising a projected film image ranged from 0.5 mm to 1.5 mm in each direction and thus although the tablet had the capacity to resolve measurements to a very high specification, when used with cine-film this specification was not realisable.

The criterion data set comprised the mean of ten repeat digitisations for each of the 35 points. The RMSD value calculated for the criterion data set accounted for the variability between these mean values and each of 10 sets of 35 points arising from the repeat digitisation process. Using the mean for each point removed what was a very small RMSD value of 0.14 mm and focused attention on the variability in the imaging systems.

From the analysis of the 35 points with both film and video based systems it was clear that the reliability with which points could be located was a function of the image quality and the resolving power of the digitising system. Image quality is effected by either cine-film grain density or video line and pixel resolution. Films of low ASA (64-100) ratings would provide finer grain and hence greater image quality but when filming dynamic actions with high framing rates relatively high ASA ratings (250-400) are required. For this study Kodak VNF ASA (250xx) was used. The sVHS video tape used has a line resolution of 400 per frame or 200 per field. The CCD camera used has a resolution of 450 horizontal lines per image and so was not the limiting factor when recording down onto sVHS tape. At the digitising stage, the resolution of the film digitising tablet was more than 100 times greater than the RMSD repeatability score of 2.7 mm. When digitising the projected image the tablet digitiser had the facility to resolve the 800 mm high image into 40 steps per mm. This is equivalent to approximately 15 bit
resolution. In comparison the video frame store had a vertical pixel resolution of 256. This is equivalent to 8 bits, \((2^{8})\). In raw resolving power the tablet digitiser is 15 bit and is therefore 128 \((2^{7})\) times better than the video system. In the horizontal direction the video frame store resolution increased by a factor of 2.5, reducing the disadvantages incurred by video slightly. Zooming the video image at the digitising stage effectively increased the resolution in \(x\) and \(y\) by a factor of two but also degraded the image quality as the pixels are simply repeated when the image is enlarged. Tests on RMSD for repeatability over a range of points and using different sized images (Table 4.8) showed that the actual performance of the film system was not limited by the equipment but more by the image quality and the operator variability. Hence the term effective resolution was introduced to examine the actual resolving power of each system. This was summarised in Table 4.7 and showed that the effective resolving power of the film based system was better than the video system by a factor of almost 4. The video system could be greatly enhanced if the pixel resolution of the frame store were to be increased and if image enhancement techniques were to be employed.

A systematic error was highlighted in Table 4.6. RMSD scores before and after image rotation showed clear improvements. Not surprisingly the criterion data did not benefit from rotation. However the improvement in film based data was approximately 100\%. For video the improvement was much less at about 20\%. These rotations reduced the influence of systematic errors arising from mis-alignment of the camera at the recording stage, and in the case of the cine-film of the projection system at the digitising stage. The angle through which the image needed to be rotated was always small and invariably less than 0.5°, however its effect was dramatic, particularly in the case of 16 mm cine-film. The mis-alignment arising from video recording and analysis is concentrated at recording stage. Small rotations of the data arising from poor camera positioning were corrected for by the image rotation but the video digitising system did not introduce a mechanical rotation of the image. Therefore the improvements in the data quality were less marked but in all cases noticeable. However, other factors need to be considered. When recording video images, the data is transferred to video tape with the tape running at standard speed, but when the images are digitised the tape is stationary in “freeze frame” mode. A modern charge couple device (CCD) video camera captures the image instantaneously, but the image is scanned onto the tape line by line and retrieved line by line at the playback stage. The fact that the image may not be scanned truly linearly and that the image is stationary rather than moving will both influence the geometry of the image and reduce its overall measurement accuracy.

The cross referencing of data reported in Table 4.8 enabled the effects of using different selections of reference points within the whole field to be investigated. It was therefore possible to determine that using a reduced set of 9 points providing that they were suitably spaced out
within the image could provide sufficient information to enable the offset, scaling and rotation factors to be satisfactorily calculated.

The accuracy results reported in Table 4.9 clearly indicated that the overall performance of cine-film was 2.5 times better than that achievable with the video system investigated. The high speed video system which would have been required to meet the frequency specifications of the jumping experiment is based on the American NTSC standard and has a lower line density (120 lines/field at 200 Hz) than the European PAL encoded sVHS tape used for this study (400 lines per field at 50 Hz). It is therefore unlikely that data of better quality could have been obtained with the high speed video system than had been obtained with the sVHS tape/Arvis frame store combination.

Cine-film therefore was selected for the visual data capture of the jumping study. Nine control points were used to obtain image origin, scaling and rotation factors. Although great care was taken in setting up the cine camera and the analysis projector for the calibration study it was clear that image rotation was essential if the overall accuracy of the measurement process was to be maximised.

4.5 SUMMARY

The purpose of this chapter was to describe a series of enabling experiments which were carried out to answer five questions in preparation for an inverse dynamic analysis of rebound vertical jumping. These questions were aimed at prescribing appropriate data recording procedures and establishing the accuracy of the force and visual recording procedures which were to be used. Questions one and two concerned the frequency characteristics of the force plate and its newly designed laboratory mounting. Question three concentrated on the accuracy of the force plate data. Questions four and five focussed upon the suitability of two different visual recording media and the measurement accuracy likely to be achievable using these two systems.

The redesign of the force plate mounting and modal analysis of the combined force plate and support structure together with independent frequency analysis of human movement indicated that a sampling frequency of 2.5 kHz was required. To avoid aliasing a suitable software filter was employed to eliminate plate resonances whilst maintaining signal fidelity. The increase in data volume arising from the long duration of the whole Marey style jumping action and the need to sample at a composite rate of 10 kHz produced problems in data handing and storage. Additional software was written to cope with these data manipulation procedures which had this experiment to be repeated with a current high specification micro-computer would no longer be necessary. The accuracy of the force plate was well within the expected range with magnitude of vertical force errors likely to be approximately 0.1% and point of force application errors near
the central part of the plate within the manufacturer's claimed figure of ±2 mm.
Visual recording capacities of two different systems were evaluated; one based on cine-film and one on video. A grid attached to a high resolution digitising tablet was used as a calibration object. Images recorded with a 16 mm cine-film camera and a CCD video camera were analysed using a tablet digitiser and video frame store respectively. Although both cine-film and video were capable of providing the high sampling rate required the markedly superior measurement accuracy of the cine-film based system made this the clear choice for the 'Marey' jump study. Also based on the results of this calibration study it was decided that fixed markers be placed in the field of view encompassing the activity area, but not encroaching too near the edges of the image. Image offset, scaling and rotation factors would be calculated from repeated digitisations of nine well spaced calibration markers and that the image would need to be corrected for camera roll error by rotating the image if maximum accuracy was to be attained. In a 2 m image field width the expected variation measured as a root mean square difference between image points and criterion data points was on average 2.4 mm across the total field and that well defined points are likely to be accurate to ±5 mm.
CHAPTER 5
COUNTER MOVEMENT AND REBOUND JUMPING

5:1 INTRODUCTION

Counter movement jumps and rebound jumps have been separately studied by many other researchers (e.g., Asmussen and Bonde-Peterson, 1974a, b; Komi and Bosco, 1978a, b; Bedi et al., 1987; Bobbert et al., 1987a, b). In Chapter 3 both styles of jumping were analysed. Marey in 1885 (cited by Asmussen and Bonde-Peterson, 1974a) observed that people appeared to be able to jump higher following a preliminary jump than when beginning from a stationary position. In this chapter a combined jumping action comprising a counter movement jump, a rebound jump and a drop landing has been used as the experimental task. A representation of the sequence is shown in Figure 5.1. In acknowledgement of the work of Marey, this jumping style has been referred to as a "Marey Jump". The main purpose of this investigation was to answer the question:

Did the height that a person jumped following a counter movement vary from that following a rebound landing?

As this particular combination of counter-movement and rebound jumping embodies many of the characteristics of previously reported research on jumping, comparisons could be made with other studies, and between the techniques adopted by the subjects within the current study. Specifically, the actions of takeoff and landing were compared. The Marey style of jump incorporates two takeoffs and two landings, but the requirements for each are different. The main question therefore was supplemented with two further questions:

(i) in what ways do the takeoff actions following a counter movement and a rebound vary?

(ii) in what ways do the landing actions preceding a rebound jump and a return to rest vary?

To answer these questions a combination of cinefilm and force plate data was used. The subject details and data collection procedures were common to all parts of the study. The results and analysis procedures have been divided into six sections. The first details the subject data. This is followed by an analysis of the cinefilm procedures and includes image scaling and correction, film speed calibration, time synchronisation of the cine-film and force plate data and the
1,2,3 = Counter Movement Jump (CMJ)
3,4,5 = Rebound Jump (RBJ)
5,6,7 = Landing (LDG)

The Marey Jump
CMJ - The Marey jump begins with a counter movement from a stationary standing position with the arms akimbo (1) followed by a counter movement into a squat position (2) and immediate leg and trunk extension into the first flight phase (3).

RBJ - From the first flight phase the subject performs a landing and immediate rebound jump passing through a squat position (4) and extending into a second flight phase (5).

LDG - Finally the subject lands from the second flight phase, dropping into a squat position (6) and returning to a stationary standing position (7).
determination of optimal filtering parameters. The third section uses the force plate data to focus on the main question by examining the variation in jump height as determined from time in flight and from the impulses generated during the takeoffs and landings for the counter-movement and rebound jumps. It extends the work from Chapter 3 by increasing the sampling frequency, incorporating an integration correction (IC) term and by using a more extensive statistical analysis to consider trial order effects. The fourth section concentrates on the frequency content of the takeoff and landing actions using the force plate data. This was designed to identify differences in the fundamental nature of the movements and to provide information for the data filtering procedures to be employed in the subsequent analyses. The remaining two sections concentrate on identifying similarities and differences between the jumping and landing actions used in this Marey style jump sequence. Section five uses the cine-film and force plate data in an inverse dynamic analysis of the individual joint contributions to each takeoff and landing action. The sixth section concentrates on the suitability of quasi-static methods for analysing vertical jumping and investigates the nature of the work done at each joint for these two jumping activities.

5:2 METHOD

Data Collection

In this study eight male subjects repeated a counter-movement jump immediately followed by a rebound jump and landing. In each trial subjects were required to make a maximal effort to jump as high as possible in both the counter movement and the rebound phases of the task. Force data for six complete jumping actions for each subject together with synchronised cine-film recordings of the third jump trial were recorded. The data collection and analysis procedures were developed from the experiences gained during the jumping study reported in Chapter 3 and incorporated the calibration and specification details outlined in Chapter 4. The aim of this experiment was to determine whether the preparatory rebounding action aided the jump performance more than the counter-movement action and if so what aspects of technique or movement sequence most influenced the outcome.

Setting

The newly designed solid mounting frame and the force plate (Kistler 9281B12) were set within a raised walkway comprising the six wooden boxes used in the drop landing experiment (Chapter 3). Each box was of height 0.15 m and with a top surface 1.2 m square. The top of the force plate was flush with the top surface of the walkway. One of the walkway boxes had a section removed from the centre to house the force plate. This "key" box was bolted to the floor to prevent it moving sideways relative to the force plate. The other sections of the walkway
were then aligned with this key box. (Details are provided in Chapter 4 Figure 4.2).

Subjects

The subjects were eight male, active physical education students, in the age range 23-28 years. In addition to their general all round physical fitness, the subjects had undertaken specialised training in a variety of sports including association football, swimming, middle distance running, gymnastics, volleyball and modern pentathlon. Standing height was determined using a stadiometer (Holtain) and body mass was recorded with a clinical scale, (Herbert and Sons Limited). Twelve surface landmarks were identified over which circular black discs were located. These were 2 cm in diameter and were either self-adhesive discs or short pieces of surgical adhesive tape onto which solid black circles were drawn with an indelible marker pen using a circular template (Helix H6701). The distances between these surface landmarks were measured using an anthropometer (Holtain). Finally a 35 mm still photograph of the subject was taken with the markers in position. The subject adopted a prescribed starting position on the force plate with feet parallel and shoulder width apart, hands on hips and facing to the right from the camera operator's view. Anthropometric inertia data were selected from the data tables of Winter (1979) and Zatsiorsky and Seluanov (1983), with supplementary anthropometric measures being extracted from A4 prints of the 35 mm photographs.

Filming

The high framing rate offered by cine-film, together with the markedly better measurement accuracy made film the clear choice for the 'Marey Jump' study. Also, based on the results of the previous calibration study reported in Chapter 4, markers were placed in the field of view to encompass the activity area for the subjects, but not to encroach near the edges of the image. The use of four fixed reference markers in the field of view was suitable for the removal of inter-frame misalignment, but offset, scaling and rotation data were calculated from nine markers equivalent to the 'D9' locations used in the calibration test (Figure 4.12c).

A 16 mm rotating prism cine-film camera (Redlake Hycam) operating at a nominal framing rate of 250 Hz was used to record a single jump performance for each subject. However, as the action to be filmed was essentially vertical and the aspect ratio of cine-film is landscape rather than portrait, the camera was rotated through 90° to make full use of the image size in relation to the direction of movement. The camera body was mounted on a rigid tripod and adjusted in height until the centre of the lens was level with the centre of a reference frame mounted on the force plate. Reference numbers were positioned in the rear-ground to identify subjects and trial numbers. In each case a single trial was filmed unless there were any problems, in which case successive trials were filmed until a satisfactory set of data had been collected.
The reference frame used was a modified two-dimensional version of the 'X' frame described by Van Gheluwe (1978). This was 2 m in overall dimension and was bolted to the force plate, by means of a 'Y' shaped mounting which had a central perpendicular spigot onto which the 'X' frame could be located. This raised the centre of the 'X' frame to a height of 1.125 m above the top surface of the force plate. Additional scaling targets 0.10 m square, (Figure 5.2), were mounted on the 'X' frame with their centres 1.5 m apart to ensure that they were in full view in both the vertical and horizontal dimensions with the focal length of the zoom lens (Schneider 15-85 mm) adjusted to approximately 20 mm. The distance between the action plane, coincident with the force plate centre, and the film image was 6.0 m, with the lens height being level with the centre of the 'X' frame. Image control points, 0.25 m versions of the targets attached to the scaling frame (Figure 5.2) were located in the rear-ground, 0.60 m behind the action plane and 0.165 m lower than the top 'X' frame marker. These were arranged at 1.65 m centres producing a 1.5 m square scale in the projected film image. Three rolls of film were used to record the jump performances for the eight subjects. Re-focusing and calibration were performed every time the film in the camera was changed. The four corner control points were in view throughout the filming of the scaling and action sequences enabling common reference points to be established during the subsequent analyses.

Protocol

For each subject's series of jump performances the filming lights were on and the subject was aware that filming was to take place in some, but not all of the jump trials. The subjects were fully aware of the maximal effort requirements of the exercise to be performed and had given informed consent. They had warmed up and in all cases had practised similar force plate jumping actions prior to the data collection session. The precise sequence was explained and demonstrated to each subject who then had time to warm up and practise until he was comfortable with the skill requirements and happy to proceed with the testing. When the subject was ready, the force plate was set into 'operate' mode, the subject then stepped onto the force plate and adopted a stationary position approximately in the middle of the plate with the body upright and hands comfortably placed on his hips. A remote trigger button was then pressed, immediately after which a verbal command to begin was issued. The subject then performed a counter-movement jump, immediate rebound jump and controlled landing, returning to a position similar to the initial standing posture. Provided that the subject was happy that his performance was a true reflection of his ability and that during the jumping sequence the subject had begun and ended in a controlled and balanced stance, without his feet making contact with the ground beyond the force plate surface, the action was regarded as successful. The third sequence in each case was filmed. All the other procedures were maintained and the cine-camera was set to run when the subject was stationary on the plate awaiting the verbal command. If the action was totally successful no further filmed sequences were recorded for
Figure 5.2. Cinefilm calibration Reference and Scaling 2D "X" frame.
that subject. In two cases one additional sequence (subjects 1 and 7), and in one case two
additional sequences (subject 8) were recorded. The final filmed sequence for each performer
was digitised and used in the later analyses. At the completion of the experiment the surface
body markers where removed and all force data transferred to backup data discs.

Force plate data

Force plate data were collected using the laboratory interface (CED1401) linked to a
microcomputer (Acorn BBC Master 128k). Force sampling was conducted at an aggregate of
10 kHz, giving 2.5 kHz for each of the four channels as specified in Table 5.1.

Table 5.1. CED1401 Laboratory Interface channel specification.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measurand</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC 0</td>
<td>Vertical Force</td>
<td>F_z</td>
</tr>
<tr>
<td>ADC 1</td>
<td>Horizontal Force</td>
<td>F_y</td>
</tr>
<tr>
<td>ADC 4</td>
<td>Point of force application</td>
<td>ay</td>
</tr>
<tr>
<td>ADC 7</td>
<td>Shutter Pulse</td>
<td>Sp</td>
</tr>
</tbody>
</table>

To facilitate synchronisation of film and force plate data a shutter output pulse from the cine-
camera was connected to the fourth analog to digital channel of the CED1401 interface.
Triggering was accomplished via a manually controlled push button contact closure detected via
the event 4 connector on the CED1401 interface, which in turn was linked to the analog to
digital converter circuitry within the interface unit. Simultaneously the vertical force and the
shutter pulse were recorded on a dual channel digital storage oscilloscope (Gould OS4200)
having a capture period set to five seconds. This enabled visual inspection and monitoring of
the vertical force signal and the film camera shutter pulse throughout the execution of the
activity. If all the conditions were satisfied then the trial was accepted.

Collecting data over a time period of almost five seconds at the specified analog data sampling
frequency of 2.5 kHz per channel generated approximately 50,000 readings per trial. Using the
CED1401 and BBC Master computer, these data had to be stored in six blocks as six separate
files for each trial for the eight subjects. Other details of the use of the extended RAM and the
software commands to handle MASSRAM data collection, together with the storage details
were achieved using the program MAREYjp (Appendix B4.1) and described in Chapter 4.
Details of the procedures followed and the programs which were used to analyse each trial and
to subdivide each trial into separate data blocks are provided in the force analysis section.
Inertia Data

Two separate sources of inertia data were used, 'W' data based on Winter (1979), which combined data from Dempster (1955) reported via Miller and Nelson (1973), Plagenhoef (1969) and Winter's own calculated values, and 'Z' data based on Zatsiorsky and Seluanov (1983 and 1992), the latter of which used non-linear regression methods. The W inertia data set have been used widely in inverse dynamic analyses of running, kicking and jumping (Winter, 1983; Robertson and Mosher, 1985; Kerwin, 1992). The Z inertia data set was regarded as more likely to be appropriate in this study since it had been generated from live physical education students similar in age and size to the subjects in this study. However, the link segment boundaries are specified differently in these two sources and so the segment lengths, masses, mass centre locations and moments of inertia are likely to vary considerably. Both inertia sets were used for all the analyses so that the influence of body segment inertia parameters on inverse dynamics analysis of jumping could be evaluated. Additional anthropometric measurements were required to enable the Z inertia data set to be completed since the head, neck and trunk segment (HNT) had been defined as four separate units in the original Zatsiorsky and Seluanov (1983) study. The four anthropometric measures required were the distances from the Vertex to the Vertebra Prominens, Xyphion, Omphalion and Symphysion as defined Zatsiorsky and Seluyanov, (1983, page 1154). These distances were obtained by digitising and scaling the A4 prints from the 35 mm photographs of the subjects in the standing position. By applying the principle of moments the new mass centre location for the HNT segment was determined. Using the scaled lengths and the parallel axes theorem the moment of inertia of the HNT segment about the transverse axis through the newly determined mass centre was calculated for each subject. (Details of these calculations have been included in Appendix A5.2). The location of the whole body mass centre was determined using a six segment model. The head, neck and trunk was treated as one segment with the feet, shanks, thighs, upper arms, and lower arms and hands as the other five segments. Again the Z data set had to be modified using the A4 prints to enable the lower arms and hands to be treated as a single segment. The mass centre location and moment of inertia of the lower arm and hand segment about the transverse axis through the mass centre were calculated.

Cinefilm data

The reduction of all the coordinate data from cine-film required that the projector (NAC DF-16C) and the digitising tablet (TDS, HR48) were accurately aligned and securely located throughout the digitisation procedures. The projector was mounted on a fixed and rigid stand with a downward inclination of 5°. The feet of the projector were recessed into accurately drilled holes to ensure consistent positioning and to prevent movement of the projector on the
surface of the stand. The digitising tablet was mounted on a heavy metal base and adjusted until its was orthogonal to the projector. Its location on the floor was marked with tape. The tablet was tilted until it rested against the end stop which was at an inclination of "85°. The overall height of the tablet was adjusted using the electrically powered lifting control, mounted in the base, until a comfortable operating position, from which the projected images could be digitised, was identified. Fine adjustments were then made using the projector's inclination control system until the image was perpendicular to the tablet surface. This was achieved using a blank image of the projector's wide aperture gate and repeated digitisations of the corners of the projected rectangle. Images were digitised once the projector and hence film were fully warmed up to avoid film stretching problems and variations in image focus.

The digitising tablet was interfaced to a microcomputer (Acorn Archimedes A3000) and the program "Cinedig (Appendix B5.1) used to collect the data. The program was written to enable long film sequences to be digitised. Dual copies of the data were written to file alternately, with the first frame being written to file A and then frames one and two being written to file B. These two files were then used alternately so that in the event of a computer failure during the digitisation process, even if it occurred during the file writing phase, only data from the most recent frame to have been digitised would be lost. To speed up data writing to disc these two master copies were stored in binary format and at the completion of the digitisation process a single ASCII text file was written to disc. In the event that an error did occur during the digitisation, and the text file therefore was not created, a second program "Convert (Appendix B5.2) was written which loaded and interpreted the binary files and wrote out the required text files. The text files were used in all the subsequent analyses.

Digitising points in the correct sequence was facilitated in two ways. Two setup files were created, one for the calibration frame and one for the movement action. These are listed in Appendices B5.1a,b. The names of the points to be digitised were displayed on the screen and at the completion of each frame a stick figure was displayed which linked the digitised points according to the drawing instructions contained within the appropriate setup file.

The data reduction process required all the body landmark data points be rotated through an angle of 90° to re-orientate the image which had been filmed with the camera in a horizontal rather than vertical position. The data were then scaled and offset such that the image data were specified in SI units with respect to an origin at the centre of the top surface of the force plate. The rotation, offset and rotation parameters for each of the three film rolls had to be determined using the 'X' frame sequence at the commencement of each film roll. These parameters were then applied appropriately to each jump performance data set.
Cinefilm Reference Data

To determine the scaling, offset and rotation parameters for each filmed sequence, a single reference image containing nine control points was digitised ten times. The selected control points were the centres of the four rearground markers, the centre of the 'X' frame and the centres of the "compass point" markers (E, N, W and S) on the limbs of the 'X' frame. However, in the processed film the centre of the 'X' frame was not as clearly identifiable as the other control points and so its location was determined by averaging the compass point marker centres. Eight points were therefore digitised. The four corner points were digitised in sequence anti-clockwise beginning in the upper left corner. The four compass points were digitised in the order E, N, W, S. This sequence was performed twice for each frame and then repeated nine times providing 20 estimates for the location of each of the eight points. The data were then pre-processed to match the originally specified nine point calibration distribution and entered into the program RMSDX9 (Appendix B5.3) to determine the scaling, offset and rotation parameters required for the subsequent movement analyses.

Cinefilm Marey Jumping Data

The movement data were digitised in three separate phases, takeoff, rebound and landing. The film of each subject's performance was inspected to locate key frames. For phase one, takeoff was identified as the first frame in which the subject lost contact with the surface of the force plate. In phase two, rebound, the final frame of downward flight and the first frame of upward flight were noted. In the landing phase the final frame of flight prior to the landing contact was identified. In the filmed sequences for subjects one and two all the frames in each phase were digitised. However, subsequent analysis showed that having the high sampling rate whilst being excellent for identifying the "key" frames at the instants of takeoff and landing, increased the digitising time dramatically without improving the overall quality of the displacement data. For all the other subjects every fifth frame for takeoff (=50 Hz) and every second frame for rebound (=125 Hz) was digitised but "key" frames were located using the full 250 Hz time resolution. For the final landing phase the initial impact was digitised at 125 Hz and the remaining part of the landing at 50 Hz. In addition to the ground contact periods in each phase, five frames when the subject was clearly in flight were digitised after takeoff and prior to landing. The start and end frames for each digitising sequence were marked to ensure precise relocation of the required images on subsequent occasions.

In each film frame the four rearground markers and twelve points on the subject's body were digitised. The twelve points on the subject's body were digitised in the order as shown in Table 5.2.
Table 5.2. Body landmark labels in order of digitising

<table>
<thead>
<tr>
<th>Number</th>
<th>Marker</th>
<th>Anatomical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>toe</td>
<td>extreme right lower great toe boundary</td>
</tr>
<tr>
<td>2</td>
<td>ball</td>
<td>5th metatarsal-phalangeal intersection</td>
</tr>
<tr>
<td>3</td>
<td>heel</td>
<td>extreme left lower heel boundary</td>
</tr>
<tr>
<td>4</td>
<td>ankle</td>
<td>lateral malleolus</td>
</tr>
<tr>
<td>5</td>
<td>knee1</td>
<td>tibial condyle</td>
</tr>
<tr>
<td>6</td>
<td>knee2</td>
<td>femoral condyle</td>
</tr>
<tr>
<td>7</td>
<td>hip</td>
<td>greater trochanter</td>
</tr>
<tr>
<td>8</td>
<td>pelvis</td>
<td>iliac crest</td>
</tr>
<tr>
<td>9</td>
<td>shoulder</td>
<td>acromio-glenoid fossa</td>
</tr>
<tr>
<td>10</td>
<td>elbow</td>
<td>lateral epicondyle</td>
</tr>
<tr>
<td>11</td>
<td>wrist</td>
<td>styloid process of ulna</td>
</tr>
<tr>
<td>12</td>
<td>ear</td>
<td>External auditory maetus</td>
</tr>
</tbody>
</table>

The four rearground markers were used as "wobble" points. That is they were used to remove the effect of the inter image mis-alignment arising from the use of a non pin registered camera and projector. The average x and y values for the four "wobble" points for each frame were calculated, (meanx and meany). In addition the average for each of these midpoints over the whole set of frames in each phase was calculated, (MEANX, MEANY). The individual frame wobble factors for x and y were then calculated as the difference between these pairs of x and y mean values and subtracted from the originally digitised body landmark values. The subsequent data were thus in the same units and to the same scale as the original data. The data were rotated through 90° to correct for the camera orientation at the filming stage. The movement data were additionally rotated, scaled into SI units and offset so that the origin coincided with the centre of the top surface of the force plate. The calibration coefficients needed to perform these transformations were specific to each film roll allowing for any slight adjustments that may have occurred in loading and re-focussing the camera or in locating and focussing the projector. The combined operation was achieved using the program dwsor9 Appendix B5.4.

Cinefilm Speed Calibration and Data Interpolation

A stroboscopic pulse train driven by the cine-film camera shutter was recorded synchronously with the force plate data. However, the recorded data were found to be intermittent and unreliable and so an alternative film speed calibration procedure was used. Variations in light intensity during the early part of each film run indicated that the Hycam camera took several seconds to attain a stable framing rate. It was therefore necessary to use a time interval, which encompassed the majority of each movement sequence, to determine the framing rate of the
camera. Two events were selected, the counter movement takeoff (TO1) and the instant of contact in the final landing (LDG2) were identifiable to the nearest film frame. The maximum timing error was therefore likely to be approximately 0.004 s (nominal framing rate = 250 Hz) at each end of the interval giving a most probable overall time interval error (E) of 0.0057 s

\[ E_t = \sqrt{E_{11} + E_{22}} \]

where \( E_t \) = time error over the interval, \( E_{11} \) and \( E_{22} \) = time errors at time (TO1) and time (LDG2).

The total time period used was typically three seconds, representing an error in quantifying the average film framing rate of approximately 0.2%. This was a worthwhile improvement in accuracy considering that the cine camera framing rate is usually no closer than ±1% to the nominal rate selected. The framing rate was checked for each film roll and for each jump sequence. A third order interpolating spline by Reinsh (1967) coded and developed by Challis (1991) was used to convert the film data to a constant 250 Hz time base. For each trial, two files, one containing the digitised coordinate data and the other the new 250 Hz time base to encompass the total activity period, were input and a new data file with the coordinate data at 0.004 s intervals was output. Synchronisation of the new film data with the force data was achieved by aligning identifiable takeoff or landing events in each movement sequence. Errors in synchronisation were also likely to be 0.004 s (ie. nearest frame).

Cinefilm Data Filtering Coefficients

Determination of a kinematic description of the different subjects' jumping actions required that linear and angular displacement, velocity and acceleration data were available. Working from digitised cine-film data, it was essential that the position data be filtered prior to differentiation to enable meaningful first and second differentials to be obtained. Two options were considered, Generalised Cross Validated Quintic Splines (GCVQS: Woltring, 1986) and Butterworth digital filtering and direct difference techniques as reported by Pezzack et al. (1977). The former technique has been shown to have considerable advantages as a general data management procedure, (Challis and Kerwin, 1988). The GCVQS offered the major advantages of overall applicability and robustness with the required smoothing parameters being automatically determined during the processing. Kerwin and Challis (1989) found that the GCVQS was particularly effective and produced the best overall acceleration results when compared with a criterion data set generated from mathematical functions with randomly generated noise added. However, the GCVQS procedure required considerable computing power to solve for the large data sets for which it was ideally suited. The alternative was the Butterworth filter followed by a central difference calculation to produce acceleration data. This combination of data smoothing and differentiation had the advantages that it required little
computing power and worked well with small data sets. The limitations associated with Butterworth smoothing option, however, were the need to select a suitable cutoff frequency and the distortion of the differentiated values at the ends of the data sets. The automatic selection of individually tuned smoothing parameters offered by the GCVQS procedure offered a major advantage. If the Butterworth option were to be used, the ground reaction force-time trace, when offset to body weight and scaled by body mass, would provide an ideal criterion data set in the form of the acceleration-time history of the motion of the whole body during each phase of the jumping action. Using the calculated mass centre to represent the motion of the whole body meant that a single smoothing parameter could be obtained for each trial and for each subject separately. However, the optimised cutoff frequency selected in this way would not necessarily be the preferred choice for each of the separate landmark coordinate time histories for each trial. The end effect problems were overcome by "padding" the data to reduce the influence of these unwanted effects, as advocated by Challis, Yeadon and Kerwin (1991).

The finally adopted data management procedures combined the best features of all the options available. The third order spline (Reinch, 1967) used for the cine-film and force plate data time synchronisation was replaced by the GCVQS (Woltring, 1986) for the main kinematic data processing. This is a multi-order interpolating, filtering and differentiating procedure. The resulting linear and angular kinematic data were then used for all subsequent analyses. The calculated motion of the mass centre for each subject generated from integration of the force time data was regarded as a criterion data against which the cine-film generated motion of the mass centre was compared. This provided a check on the accuracy of the processing which the cine-film data had been subjected too. It did not facilitate separate evaluations of the digitising, scaling, offset and rotation processes nor of the filtering and differentiation effects of the GCVQS, but it did provide a single quantifiable independent measure of the net effects of all these processes.

Cinefilm Kinematic Data

Kinematic data describing each jump were generated in two ways. Firstly the output from the GCVQS was used directly and secondly it was subjected to additional post differentiation smoothing using a Butterworth filtering 4th order routine with padded end point data and a single cutoff frequency ($f_c$). This single $f_c$ was selected by minimising the differences between the whole body mass centre acceleration time history and the directly measured vertical force time history with the appropriate offset for body weight and body mass scaling. The data output from the spline routine comprised, landmark and segment mass centre locations and segment angles, together with first and second differentials of these with respect to time. Comparison of the output from these two processes provided information on the influence of Butterworth Filtering on the subsequent resultant muscle moment, power and energy values.
Joint Angle Definition

Defining the knee and hip angles was essential to the later inverse dynamic analyses. Problems arose since there were two knee joint markers and several options for defining the angle of the upper body. To determine a single knee joint centre, the intersection of the lines defining the shank and thigh segments was used. The angle of the shank segment was defined by the line joining the ankle joint centre with the lower knee marker. The thigh segment was defined as the line joining the upper knee marker with the hip joint centre. Throughout the majority of the motion there was a unique point of intersection at the "knee". However, as the leg approached full extension the two leg segment lines did not necessarily intersect within the region of the knee joint. Under these circumstances the knee joint centre was defined as the mid point of the two knee markers. Two options were considered to define the angle of the upper body. Either the mass centre for the whole upper body, referred to as Head, Neck, Arms and Trunk or 'HAT' by Winter (1979), could be calculated and then the angle of the trunk be defined by the line joining the hip to the HAT mass centre. Alternatively, the head, neck, trunk and arms could be assumed to be fixed relative to each other throughout the action and a line joining the hip to a fixed point on the HAT segment could be used to represent the angle of the upper body. Two options were possible for the latter case, either the vertex of the head or the shoulder joint centre could be used. Bobbert et al., (1987a, b) used a marker on the neck to define the upper boundary of the HAT segment. However, observation of the filmed recordings of subjects indicated that during landing and jumping, the subjects adjusted the head position, probably to improve vision of the ground and so the motion of the head was likely to alter the mass centre location of the HAT segment. The shoulder joint, although generally quite difficult to locate when digitising normal human movements was readily defined in this study since the arms were kept akimbo throughout the motion. The shoulder joint centre surface marker was therefore in view throughout the sequence. All three trunk angle options were compared to investigate the influence of head and arm movements on the resulting hip angle and hip joint angular velocity data.

Force plate data

Three sets of programs were used to analyse the force plate data. Initially program 'Marey', Appendix B5.5, was used to convert all binary coded digital data to Newton and metre units and store them in 'real' number format. Graphical presentation on the screen was linked to a mouse controlled cursor for the selection of the initial and final points over which integration was conducted. These points corresponded to the Newton value which most closely matched the subject's body weight whilst the $F_2$ force curve was horizontal. To check the frequency content of the force data, three 4kbyte windows of data, one for each phase of the Marey jump were
stored in 16 bit binary format for Fourier analysis. These were subsequently analysed using programs MareyPSD (Appendix B5.6) and FFTnrgM (Appendix B5.7). The raw data were searched to determine the key times, $T_0$ to $T_5$ as listed in Table 5.3.

### Table 5.3. Key times ($T_0$ to $T_5$) from the force time trace of a Marey Jump sequence

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>Start of the movement sequence</td>
</tr>
<tr>
<td>$T_1$</td>
<td>Take-off for flight phase 1</td>
</tr>
<tr>
<td>$T_2$</td>
<td>Landing from flight phase 1</td>
</tr>
<tr>
<td>$T_3$</td>
<td>Take-off for flight phase 2</td>
</tr>
<tr>
<td>$T_4$</td>
<td>Landing from flight phase 2</td>
</tr>
<tr>
<td>$T_5$</td>
<td>End of the movement sequence</td>
</tr>
</tbody>
</table>

Takeoff and landing events were defined in the same way as in Chapter 3, with the force threshold being set at $\frac{1}{2}$LSB of the ADC. A force of at least 25 N was therefore required to indicate ground contact. Each graph was divided into six sections, two takeoffs, two flight phases and two landings. Takeoff one ($T0_1$) was defined as the counter movement jump takeoff. Takeoff two ($T0_2$) occurred from the rebound phase of the jump sequence. Flight phase one ($Ft_1$) was between times $T_1$ and $T_2$ and flight two ($Ft_2$) from $T_3$ to $T_4$. Landing one ($LDG_1$) was the landing part of the rebound jump and landing two ($LDG_2$) was the final landing following flight two ($Ft_2$). $T0_1$ and $LDG_2$ could be calculated directly from the force data using numerical integration. $LDG_1$ was the impulse necessary to bring the subject to momentary rest following the first flight ($Ft_1$). $T0_2$ impulse was the impulse necessary to accelerate the subject up to takeoff 2. The remaining area, termed here the "Support Impulse" was the rectangular area under the weight force line for the support period. This is strictly not an impulse since there would be no change in momentum but has been termed the support impulse for convenience to match with the two other impulse components of the total rebound impulse (RI).

Since RI could be calculated by integrating over the ground support time (GST), that is between $T_2$ and $T_3$ with reference to a zero datum line and SI was known from body weight and GST, the remaining impulse had to be shared between $LDG_1$ and $T0_2$. The sharing of this remaining impulse was not possible without additional information. It was important therefore to determine how accurately flight times and impulse values matched. If the assumption that the takeoff velocity arising from impulse $T0_1$, and takeoff velocity calculated from $Ft_1$ were equal, the impulse from $LDG_1$ would equal the takeoff impulse $T0_1$. Similarly, $Ft_2$ could be used to predict takeoff and landing velocities for the rebound jump and final landing. These velocities would only be identical if the body position of the subject was identical at takeoff and landing. This is unlikely, but as shown in Chapter 3, the relationship between the height jumped for a counter movement jump calculated from impulse and flight time was very close to linearity ($r=0.95$). In the current experiment the sampling rates had been increased by a factor of five.
from 500 Hz to 2500 Hz. It was therefore likely that the errors associated with approximating
the force time curve as a series of straight line segments were likely to be reduced as shown in
Figure 3.5. However, the effects of the IC term, ignored in Chapter 3, needed to be determined.
A series of calculations were conducted. Each subject began and ended in a stationary standing
position. Thus, for the vertical force-time trace ($F_{zt}$), the net impulse, with respect the the body
weight line, should have been zero. A complete trial lasted just under five seconds and
contained 12,288 (12 kbytes) force readings per channel. It was therefore reasonable to assume
that any quantisation errors, albeit small in amplitude at less than 1 part in 8192, would have
been randomly distributed about a mean of zero. For each trial IC was calculated using the
vertical force record from time zero to a time of approximately 4.9 s. Only trials in which the
subject started and ended in a stationary standing position were used. The weight of the subject
had been determined independently using clinical scales (Herbert and Sons Limited) and so the
vertical force integration datum line (the subject's weight) had been accurately located. A non
zero value in net impulse was therefore assumed to be an accumulation of the effects of an
unknown integration correction. By dividing the non-zero momentum at the end of the
integration process by the total time over which the integration had been calculated, a small
constant value was determined. This was then used as an offset in the integration process which
was repeated to determine all the other parameters including takeoff and landing velocities.

Heights jumped were calculated from the velocities at takeoff and used as a measure of jump
performance. All time values were based on the 2.5 kHz sampling frequency giving a time
resolution of 0.0004 s. Thus for the CMJ style of jump, three jump height figures were
obtained; one based on time of flight (CMJt), one based on integration (CMJi) and a third based
on integration following offset correction using the IC term (CMJic). Similarly three heights
were calculated from the force time data for landing two, (LDG2t, LDG2i and LDG2ic). Finally,
using the rebound and support impulse data, and the results of the takeoff and landing analysis,
the remaining rebound impulse was shared between LDGt and TOs so that the takeoffs for the
CMJ and the RBJ actions could be compared. Three estimates of jump height were obtained;
one based on flight times, the second and third based on integration but with the latter including
the correction of integration. These were labelled CMJt and RBJt, CMJi and RBJi and CMJic
and RBJic. The eight subjects performed six trials each. Two Way Analysis of Variance with a
repeated measures design was used to investigate differences between jump types, trials and
calculation methods. Linear Regression was used to investigate the correlation between the
integration based, and time based, calculations of jump height.
Figure 5.3. The six sections of the 'Marey' style jump.
Fourier Analysis

Three 4 kbyte force-time data sub-files, created by program Marey, (Appendix 5.5), one for takeoff, one for rebound and one for landing, were subjected to Fourier analysis. The files were padded with data to ensure that they were all 4 bytes in size in preparation for the Fast Fourier Transformation. The takeoff file started with body weight values and ended with zero values. The landing files were the opposite way around with the initial values being zero and the final ones being body weight. Each of these phases was longer that the required 1.64 s necessary to produce 4096 readings at 2.5 kHz. The rebound phase however varied in duration for each subject and never reached the maximum size of the required array. The files were padded with zeros at the beginning and end so that the the rebound force trace remained in the centre of the data window. The files were loaded from disc and transferred into the CED1401 interface where a 4K version of the discrete FFT routine to handle 4096 readings per channel was used. The force and centre of pressure data were filtered with the "inbuilt" bi-linear routine, which has frequency characteristics almost identical to the Butterworth technique used with the cinefilm data. The cut-off frequency was set at 0.1024 times the sampling frequency \( f_c = f_s \times 0.1024 = 2500 \times 0.1024 \) giving an effective cut-off of 256 Hz. This value ensured attenuation of any force plate resonances whilst maintaining the integrity of the movement data. Impulse and hence velocity values were obtained by numerical integration of the vertical and horizontal force time traces. Integration was performed by numerical quadrature using the trapezoidal rule with a time base of 0.0004 s. As evidenced in Chapter 3, the use of this very narrow time slice meant that the errors arising from approximating the area under the force-time curve were minimised.

The smoothed data were then windowed with a raised cosine of amplitude 32762 (equivalent to 96 dB) to reduce the spectral smearing effects associated with discrete transforms of the type employed in CED1401 system and to reduce the influence of the Gibbs effect, described by Ramirez (1985). The resulting real and imaginary components were treated in two separate ways.

Power Spectrum

Program MareyPSD, (Appendix 5.6) was used to calculate the power spectrum for each data set using the CED1401 inbuilt command GAINPH,G. This changed the FFT coefficient display into one of log amplitude and phase. The phase information was not of interest in this study, but the power spectrum, appearing in the lower half of the data array, provided a measure of the Log power of each component in the transformed array. This resulting power spectral density (PSD) plot provided a clear indication of the frequency content of each of the jumping actions for the eight subjects. Finally a mean PSD plot was generated for each phase of each jump for the eight
subjects. Using the same FFT procedures the signal energy was also calculated to determine the relative contribution of each of the identified frequency components to the overall spectrum.

Signal Energy

Signal energies were calculated using program FFT\_nrgM, (Appendix B5.7). This repeated all the stages of MareyPSD until the Fourier coefficients were determined and then squared each term and summed the real and imaginary squared components over the whole array up to the cut-off frequency limit of 256 Hz. The percentage contribution to the total signal energy for each phase of each jump was determined by expressing the "area so far" function from the first harmonic up to the filter limit as a percentage of the previously calculated total area. Since the rebound phase of the jump included both a takeoff and a landing, this was selected as the best single representative sample for analysis. Data from the vertical and horizontal force time traces were included in the calculations, but the contribution from the horizontal component was always less than one percent and so for the remaining phases of the separate takeoffs and landings, the analysis was restricted to the vertical force data. These energy profiles were averaged over the six trials for each of the three phases of the jumping action for each subject. In addition, the individual trial used in the film analysis was also analysed for signal energy to determine if this was a representative trial for the subject in question.

The results of the Fourier analyses provided a description of the jumping activities in the frequency domain rather than the time domain. It also provided valuable information about the relative contribution of the lower frequency components present in the movement spectrum for this complex jumping sequence. Winter et al. (1974) described frequency profiles for gait analysis which have been used widely to justify the use of low pass filters when processing cinefilm and video data. Similar spectral data, for the complex jumping activities under investigation were not available, although evidence from Lees (1980) has regularly been quoted (Ingen Schenau et al. 1985; Bobbert et al. 1986; Fukashiro et al. 1993) in support of using cutoff frequencies of around 10-16 Hz.

Inverse Dynamic Analysis

The methods pioneered by Elftman (1939, 1940), modified by Bresler and Frankel (1950), and used extensively by Winter (1980,1983) were programmed for the inverse dynamic analysis of the jumps. The required inputs were subject inertia data, linear and angular kinematic data and synchronised external force data. The direct output data were resultant joint forces, and resultant muscle moments at the ankle, knee and hip joints. Lower limb support moments as defined by Winter (1980) were calculated from the individual lower limb joint moments. Additionally, by combining the joint muscle moments with the joint angular velocities, muscle
moment power values for each contributing joint were calculated. Finally the resulting power time histories were integrated with respect to time to obtain work done at each of the joints. The integration process was carried out to calculate the separate negative (eccentric) and positive (concentric) work and the net work done throughout the three phases of the Marey jump. Work was regarded as negative if the area under the power time curve was below the zero line and positive if above the zero line. A four rigid linked segmental model, comprising foot, shank, thigh and HAT, was used. Each segment was treated as a free body and Newtonian mechanics were applied to determine the resultant inter-segment forces and hence resultant muscle moments acting about each joint. Calculations began at the foot segment, using the ground reaction force data obtained from the force plate. Using Newton's second law \((F = ma)\) it was possible to calculate the resultant vertical and horizontal forces acting at the ankle joint centre. Then by applying moments about the segment mass centre, the resultant moment about the ankle was obtained using the angular equivalent of Newton's second law \((\tau = I\alpha)\). By applying Newton's third law, the resultant forces at the joint centres \((F_{z_i} \text{ and } F_{y_i})\) could be transferred from segment \(i\) to segment \(i+1\), by reversing the sign. Hence the resultant forces at joints \(i+1\) and \(i+2\) could be calculated. Similarly, the resultant moments about each joint could be reversed and transferred through the linked system from ankle to knee and hip.

Quasi-Static Analysis

The quasi-static technique as described by Alexander and Vernon (1975) was used. Modifications were made to the original specifications to avoid drawing individual cine-film frame images and marking on scaled force vectors and moment arms. The vertical force, horizontal force and point of force application values were synchronised with the lower limb cine-film landmark coordinates for each frame to calculate ankle, knee and hip moment time histories throughout each phase of the Marey jumping sequence. Inertia data were not required for this analysis, but the effects of data smoothing on the locations of the landmark coordinates were investigated. The cutoff frequency determined for the inverse dynamic analysis was used in this analysis also. The individual joint moment, and joint power and work calculations were conducted using the quasi-statically determined muscle moment values. Finally RMS differences between the results from the inverse dynamic and quasi-static analyses were calculated and comparisons between the power and energy calculations were made for each phase of the jump.
5:3 RESULTS

Introduction

The results have been sub-divided into six sections beginning with the subject details and the development of the body segment inertia parameters. This is followed by the film analysis including segment angle determination, interpolation and force plate data synchronisation, sampling frequency comparisons and filtering coefficient determination. The third section contains the force plate data analysis and includes the determination and comparison of jump heights from flight times and integration with and without a correction of integration. This is followed by frequency analyses of the force plate data. The fifth section contains the inverse dynamic analyses, with the examination of the influence of different inertia data sets and data filtering on muscle moment time histories and joint energy contributions in takeoffs and landings. The sixth section examines the quasi-static methods for calculating muscle moments and the influence of data smoothing on joint centre coordinates and concludes with comparisons between the muscle moments, power and joint energy contributions using the two different methods of calculating muscle moments.

5:3.1 Subject Data

Body segment inertia parameters

The general descriptions of the eight male physical education students, including mass, height, sport background and the filmed trial number, have been summarised in Table 5.4. The distances between the surface landmarks, measured directly from the subjects, have been included in Table 5.5. Three selected limb lengths (shank L₅, thigh L₇ and upper arm L₁₁) were used as a means of independently assessing the digitising, scaling, offset and rotation accuracy of the cine-film derived data. These values have been summarised in Table 5.6.

Table 5.4. Subject details including, mass, height, sport activity and filmed trial number.

<table>
<thead>
<tr>
<th>No.</th>
<th>Initials</th>
<th>Mass (kg)</th>
<th>Height (m)</th>
<th>Sport</th>
<th>Film Trial No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AAC</td>
<td>73.10</td>
<td>1.710</td>
<td>Football</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>RED</td>
<td>71.30</td>
<td>1.770</td>
<td>Pentathlon</td>
<td>3*</td>
</tr>
<tr>
<td>3</td>
<td>DDA</td>
<td>67.95</td>
<td>1.786</td>
<td>Triathlon</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>GCG</td>
<td>75.85</td>
<td>1.825</td>
<td>Volleyball</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>AKS</td>
<td>59.75</td>
<td>1.703</td>
<td>Runner</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>CP</td>
<td>75.00</td>
<td>1.771</td>
<td>Swimmer</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>DJS</td>
<td>62.90</td>
<td>1.712</td>
<td>Runner</td>
<td>4*</td>
</tr>
<tr>
<td>8</td>
<td>MMK</td>
<td>66.50</td>
<td>1.719</td>
<td>Gymnast</td>
<td>5*</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>69.04</td>
<td>1.750</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>St.Dev.</td>
<td>±5.80</td>
<td>±0.045</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*trials which could not be analysed due to film chemical processing failure
Table 5.5. Anthropometric Dimensions (m) of the 8 male subjects.

<table>
<thead>
<tr>
<th>SUBJECTS</th>
<th>AAC1</th>
<th>RED2</th>
<th>DDA3</th>
<th>GCG4</th>
<th>AKS5</th>
<th>CJP6</th>
<th>DJS7</th>
<th>MMK8</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.256</td>
<td>0.262</td>
<td>0.267</td>
<td>0.270</td>
<td>0.257</td>
<td>0.270</td>
<td>0.276</td>
<td>0.270</td>
</tr>
<tr>
<td>L2</td>
<td>0.151</td>
<td>0.262</td>
<td>0.163</td>
<td>0.174</td>
<td>0.157</td>
<td>0.164</td>
<td>0.163</td>
<td>0.165</td>
</tr>
<tr>
<td>L3</td>
<td>0.052</td>
<td>0.048</td>
<td>0.043</td>
<td>0.044</td>
<td>0.047</td>
<td>0.054</td>
<td>0.048</td>
<td>0.052</td>
</tr>
<tr>
<td>L4</td>
<td>0.136</td>
<td>0.128</td>
<td>0.137</td>
<td>0.132</td>
<td>0.162</td>
<td>0.134</td>
<td>0.130</td>
<td>0.123</td>
</tr>
<tr>
<td>L5</td>
<td>0.408</td>
<td>0.440</td>
<td>0.423</td>
<td>0.427</td>
<td>0.389</td>
<td>0.407</td>
<td>0.412</td>
<td>0.393</td>
</tr>
<tr>
<td>L6</td>
<td>0.047</td>
<td>0.040</td>
<td>0.055</td>
<td>0.053</td>
<td>0.028</td>
<td>0.026</td>
<td>0.031</td>
<td>0.031</td>
</tr>
<tr>
<td>L7</td>
<td>0.344</td>
<td>0.357</td>
<td>0.393</td>
<td>0.392</td>
<td>0.342</td>
<td>0.369</td>
<td>0.351</td>
<td>0.343</td>
</tr>
<tr>
<td>L8</td>
<td>0.449</td>
<td>0.450</td>
<td>0.449</td>
<td>0.463</td>
<td>0.436</td>
<td>0.445</td>
<td>0.417</td>
<td>0.397</td>
</tr>
<tr>
<td>L9</td>
<td>0.531</td>
<td>0.549</td>
<td>0.536</td>
<td>0.562</td>
<td>0.530</td>
<td>0.552</td>
<td>0.532</td>
<td>0.511</td>
</tr>
<tr>
<td>L10</td>
<td>0.253</td>
<td>0.252</td>
<td>0.247</td>
<td>0.235</td>
<td>0.223</td>
<td>0.248</td>
<td>0.220</td>
<td>0.229</td>
</tr>
<tr>
<td>L11</td>
<td>0.291</td>
<td>0.291</td>
<td>0.309</td>
<td>0.332</td>
<td>0.298</td>
<td>0.314</td>
<td>0.301</td>
<td>0.283</td>
</tr>
<tr>
<td>L12</td>
<td>0.267</td>
<td>0.274</td>
<td>0.280</td>
<td>0.295</td>
<td>0.251</td>
<td>0.273</td>
<td>0.262</td>
<td>0.258</td>
</tr>
</tbody>
</table>

Length Codes

- **L1**: Heel to Tip of Great Toe
- **L2**: Heel to Metatarsal-Phalangeal
- **L3**: Heel to Lateral Maleolus
- **L4**: Lateral Maleolus to Metatarsal-Phalangeal
- **L5**: Lateral Maleolus to lateral epicondyle
- **L6**: Lateral epicondyle to femoral epicondyle
- **L7**: Femoral epicondyle to greater trochanter
- **L8**: Pelvic crest to acromium
- **L9**: Greater trochanter to acromion process
- **L10**: Acromium to ear
- **L11**: Acromium to elbow
- **L12**: Elbow to wrist

Table 5.6. Cine-film image scaling, offset and rotation accuracy.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Criterion</th>
<th>Film</th>
<th>Criterion</th>
<th>Film</th>
<th>Criterion</th>
<th>Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC1</td>
<td>0.408</td>
<td>0.401</td>
<td>0.344</td>
<td>0.341</td>
<td>0.291</td>
<td>0.256</td>
</tr>
<tr>
<td>DDA3</td>
<td>0.423</td>
<td>0.410</td>
<td>0.393</td>
<td>0.405</td>
<td>0.309</td>
<td>0.269</td>
</tr>
<tr>
<td>GCG4</td>
<td>0.427</td>
<td>0.421</td>
<td>0.392</td>
<td>0.401</td>
<td>0.332</td>
<td>0.294</td>
</tr>
<tr>
<td>AKS5</td>
<td>0.389</td>
<td>0.381</td>
<td>0.342</td>
<td>0.352</td>
<td>0.298</td>
<td>0.282</td>
</tr>
<tr>
<td>CJP6</td>
<td>0.407</td>
<td>0.432</td>
<td>0.369</td>
<td>0.355</td>
<td>0.314</td>
<td>0.249</td>
</tr>
</tbody>
</table>

Film Data reported as mean over filmed sequence, ±Standard Deviation in brackets.

Differences between Criterion and Film Segment lengths (m)

<table>
<thead>
<tr>
<th></th>
<th>L5</th>
<th>L7</th>
<th>L11</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC1</td>
<td>-0.007</td>
<td>0.003</td>
<td>-0.035</td>
</tr>
<tr>
<td>DDA3</td>
<td>-0.013</td>
<td>0.012</td>
<td>-0.040</td>
</tr>
<tr>
<td>GCG4</td>
<td>-0.006</td>
<td>0.009</td>
<td>-0.038</td>
</tr>
<tr>
<td>AKS5</td>
<td>-0.008</td>
<td>0.010</td>
<td>-0.016</td>
</tr>
<tr>
<td>CJP6</td>
<td>0.025</td>
<td>-0.014</td>
<td>-0.065</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.002</td>
<td>0.003</td>
<td>-0.039</td>
</tr>
<tr>
<td>Mean (Absolute)</td>
<td>0.012</td>
<td>0.009</td>
<td>0.037</td>
</tr>
</tbody>
</table>
Segments L5 and L7 (shank and thigh) moved approximately within a vertical plane throughout the jumping sequence, whilst L11 (upper arm) tended to move towards the camera during the action. Segment L11 was consistently underestimated in length (-0.039 m) indicating that the upper arm segment had been foreshortened in the image analysis. Although this was not a problem in the mass centre analyses, it was not appropriate when judging the accuracy of the film image processing. Segments L5 and L7 only were used for this evaluation. Data in Table 5.4 shows that the mean errors over each sequence ranged from +25 mm to -14 mm with overall means of -2 mm for L5 and +3 mm for L7 for the five subjects analysed. These represented mean errors of <1% in relation to the criterion lengths. The worst case results in Table 5.4 indicated possible transformation errors of +6% and -4%, which indicated that other factors, including skin marker movement contributed to these relatively large errors. Cappozzo et al. (1993) reported skin marker movement artifacts for 3D analysis of between 10 mm and 20 mm, which convert to approximate length errors in 2D of between 3% and 4% in the current analysis. It would appear therefore that the film data obtained were comparable in accuracy with previously published results (Kennedy et al. 1989; Angulo and Dapena, 1992) and provided confidence in the film processing transformations used.

Segmental inertia data for the HAT segment were calculated for the W data set (Winter, 1979) by combining the head, neck, trunk, upper arm, forearm and hand values. For the Z data set (Zatsiorsky and Seluanov, 1983) additional calculations were needed to transform the original proximal ratio data from the anthropometric measures to those used in the current study. For example, the foot segment in the Zatsiorsky and Seluanov (1983) study was referenced to the length of the foot from heel to toe (L1), whereas in the current study to match the Winter (1979) data, the values were expressed with respect to the length from the ankle to the metatarsal-phalangeal joint (L4). The W inertia data sets for segments (foot, shank, thigh, trunk, upper arm and forearm plus hand) and for the head, neck, arms and trunk segment (HAT), have been obtained from Winter (1979) and reported in Table 5.7. The corresponding Z data, for this latter limbless segment, have been calculated from the segmental inertia values contained in columns 4-6, the coordinate data obtained from the digitised cinefilm and the additional trunk and arm lengths necessary to generate the HAT and Lower Arms and Hands (LAH) segments for the Zatsiorsky and Seluyanov (1983) mass centre and moment of inertia data. (The additional measurements and moment of inertia calculations were based on A4 photographic images as shown in Appendices 5.2). Each subject's HAT segment mass ratio (m_p) was obtained by summing the contributing segment mass ratios. The mass centre proximal ratio (r_p) was calculated by applying the principle of moments to determine the HAT segment mass centre location and then expressing the distance between the hip landmark and the mass centre as a ratio of the hip to shoulder distance. The radius of gyration ratio with respect to the segment mass centre (k_p) was calculated using the parallel axes theorem to determine the moment of inertia of the HAT segment about a transverse axis through the calculated mass centre location.
### Table 5.7. Body Segment Inertia Parameters, (Mean values based on the digitised trials of five subjects).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Feet</th>
<th>Shanks</th>
<th>Thighs</th>
<th>Trunk</th>
<th>UAs</th>
<th>FAHs</th>
<th>HAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter (W) Inertia Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r_m )</td>
<td>0.0290</td>
<td>0.0930</td>
<td>0.2000</td>
<td>0.5780</td>
<td>0.0560</td>
<td>0.0440</td>
<td>0.6780</td>
</tr>
<tr>
<td>( r_p )</td>
<td>0.5000</td>
<td>0.4330</td>
<td>0.4330</td>
<td>0.6600</td>
<td>0.4360</td>
<td>0.6820</td>
<td>0.6260**</td>
</tr>
<tr>
<td>( k_c )</td>
<td>0.4750</td>
<td>0.3020</td>
<td>0.3230</td>
<td>0.5030</td>
<td>0.3220</td>
<td>0.4680</td>
<td>0.4960**</td>
</tr>
<tr>
<td>Zatsiorsky (Z) Inertia Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r_m )</td>
<td>0.0274</td>
<td>0.0866</td>
<td>0.2833</td>
<td>0.5040</td>
<td>0.0541</td>
<td>0.0448</td>
<td>0.6029*</td>
</tr>
<tr>
<td>( r_p )</td>
<td>0.5590*</td>
<td>0.4050</td>
<td>0.4549</td>
<td>0.5602*</td>
<td>0.4498</td>
<td>0.6695*</td>
<td>**</td>
</tr>
<tr>
<td>( k_c )</td>
<td>0.4283*</td>
<td>0.2750</td>
<td>0.2670</td>
<td>0.5079*</td>
<td>0.3100</td>
<td>0.4472*</td>
<td>0.4719**</td>
</tr>
</tbody>
</table>

where \( r_m \) = ratio of segment mass to whole body mass
\( r_p \) = ratio of segment length to mass centre from proximal end of segment
\( k_c \) = ratio of segment length from the segment mass centre to radius of gyration
UA = Upper arm, FAH = Forearm and hand, HAT = Head arms and Trunk

* = values which were calculated from anthropometric data and averaged over the five filmed subjects.
** = values which were calculated for each subject throughout the jumping action based on the coordinate data obtained via digitisation.

As subjects upper limbs, head and trunk segments moved slightly relatively to each other during the jumping sequence, all HAT values were calculated from the segmental data for individual digitised filmed images.

### Table 5.8. Zatsiorsky and Seluanov Moment of Inertia data for the Head, Neck, Arms and Trunk segment, (Values based on the digitised trials for five subjects).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Body Mass (kg)</th>
<th>Moment of Inertia (kg.m²)</th>
<th>( k_c )</th>
<th>( k_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td></td>
<td></td>
<td>hip to shoulder</td>
<td>to shoulder</td>
</tr>
<tr>
<td>AAC1</td>
<td>73.10</td>
<td>3.0627</td>
<td>0.2636</td>
<td>0.4713</td>
</tr>
<tr>
<td>DDA3</td>
<td>67.95</td>
<td>2.7389</td>
<td>0.2585</td>
<td>0.4714</td>
</tr>
<tr>
<td>GCG4</td>
<td>75.85</td>
<td>3.4872</td>
<td>0.2760</td>
<td>0.4724</td>
</tr>
<tr>
<td>AKS5</td>
<td>59.75</td>
<td>2.3965</td>
<td>0.2579</td>
<td>0.4730</td>
</tr>
<tr>
<td>CJP6</td>
<td>75.00</td>
<td>3.0710</td>
<td>0.2606</td>
<td>0.4716</td>
</tr>
<tr>
<td>Mean</td>
<td>70.33</td>
<td>2.9513</td>
<td>0.2633</td>
<td>0.4719</td>
</tr>
<tr>
<td>St.Dev</td>
<td>6.66</td>
<td>0.4083</td>
<td>0.0074</td>
<td>0.0007</td>
</tr>
<tr>
<td>CoVar</td>
<td>9.47%</td>
<td>13.83%</td>
<td>2.82%</td>
<td>0.16%</td>
</tr>
</tbody>
</table>

Emboldened number in column 5 used in column 7 of Table 5.7
This value was divided by the HAT segment mass to obtain the radius of gyration with respect to the segment mass centre and expressed as a proportion of the distance between the hip and shoulder landmarks. Table 5.8 contains a summary of these moment of inertia calculations for the Zatsiorsky and Seluanov (1983). Although individual HAT mass centre locations and hence radius of gyration values ($K_c$) were calculated for each subject for each frame separately, the ratio value ($k_c$) for the radius of gyration distance measured from the HAT mass centre and expressed as a ratio of the trunk segment length (hip to shoulder, $L_9$) was found to be consistent for all subjects across all frames. The mean value was 0.4719 with a standard deviation of ±0.0007 giving a coefficient of variation of <0.2%. A single value was provided in the Winter (1979) data of 0.4960.

5:3.2 Cine-film Data - segment angles, filtering and synchronisation

Data Scaling and synchronisation

The raw digitised data were transformed into SI units, offset, scaled and rotated using the values in Table 5.9. These values had been obtained using the 9 point calibration system and program dwso9 (Appendix B5.4). The twelve digitised points in SI units with respect to an origin at the centre of the force plate had been digitized at different time intervals varying from every frame to every fifth frame. It was necessary to interpolate all data sets onto a common timebase and to calculate the framing rates for each sequence. The force plate data were used as the accurate 250 Hz timebase. For each digitized film sequence the key points of Start, Takeoff 1, Landing 1, Takeoff 2, Landing 2 and End had been identified during the digitisation process.

Table 5.9. Offset, scaling and rotation values based 9 point calibration routine for five filmed subjects.

<table>
<thead>
<tr>
<th></th>
<th>xoff (m)</th>
<th>yoff (m)</th>
<th>scx</th>
<th>scy</th>
<th>rotation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC4</td>
<td>-0.0131</td>
<td>-0.6109</td>
<td>249.83</td>
<td>249.29</td>
<td>+0.00</td>
</tr>
<tr>
<td>DDA3</td>
<td>-0.0240</td>
<td>+0.1351</td>
<td>252.21</td>
<td>251.77</td>
<td>-0.57</td>
</tr>
<tr>
<td>GCG3</td>
<td>-0.0224</td>
<td>+0.1366</td>
<td>253.61</td>
<td>252.89</td>
<td>-0.47</td>
</tr>
<tr>
<td>AKS3</td>
<td>-0.0224</td>
<td>+0.1366</td>
<td>253.61</td>
<td>252.89</td>
<td>-0.47</td>
</tr>
<tr>
<td>CJP3</td>
<td>-0.2700</td>
<td>-0.6144</td>
<td>253.61</td>
<td>252.89</td>
<td>-0.47</td>
</tr>
</tbody>
</table>

Frame Rate

In each force record the key times corresponding to Takeoff 1 and Landing 2 had been determined from the force plate data. These values had ten times the time resolution of the cinefilm data (0.0004 s compared to 0.004 s). Using the accurately determined time between the $T_1$ and $T_4$ from the force plate data and the number of cinefilm frames between these two key times, the corrected framing rate was determined. In Table 5.10 the subjects have been
identified by initials, subject number and filmed trial number. In addition the film roll numbers (#0, #1 and #2) have been included together with the frame numbers corresponding to these key times. The lower part of Table 5.10 contains the force plate times, the effective framing rate based on the force plate times and the corrected framing rate and the percentage differences between the nominal and corrected framing rates for each film roll and for each sequence.

Table 5.10. Film speed calibration data.

<table>
<thead>
<tr>
<th>Subject</th>
<th>AAC14</th>
<th>DDA33</th>
<th>GCG43</th>
<th>AKS53</th>
<th>CJP63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Roll #</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Start</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Takeoff 1</td>
<td>189</td>
<td>116</td>
<td>131</td>
<td>210</td>
<td>205</td>
</tr>
<tr>
<td>End dig</td>
<td>194</td>
<td>141</td>
<td>156</td>
<td>230</td>
<td>210</td>
</tr>
<tr>
<td>Start dig</td>
<td>313</td>
<td>218</td>
<td>250</td>
<td>309</td>
<td>340</td>
</tr>
<tr>
<td>Landing 1</td>
<td>318</td>
<td>228</td>
<td>260</td>
<td>319</td>
<td>345</td>
</tr>
<tr>
<td>Takeoff 2</td>
<td>428</td>
<td>352</td>
<td>376</td>
<td>504</td>
<td>498</td>
</tr>
<tr>
<td>End dig</td>
<td>433</td>
<td>362</td>
<td>386</td>
<td>514</td>
<td>503</td>
</tr>
<tr>
<td>Start dig</td>
<td>547</td>
<td>430</td>
<td>465</td>
<td>602</td>
<td>633</td>
</tr>
<tr>
<td>Landing 2</td>
<td>552</td>
<td>455</td>
<td>495</td>
<td>612</td>
<td>638</td>
</tr>
<tr>
<td>End</td>
<td>557</td>
<td>570</td>
<td>685</td>
<td>853</td>
<td>643</td>
</tr>
<tr>
<td>Time (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (CF)</td>
<td>1452</td>
<td>1356</td>
<td>1456</td>
<td>1608</td>
<td>1732</td>
</tr>
<tr>
<td>FP T1</td>
<td>1158</td>
<td>0899</td>
<td>0907</td>
<td>1387</td>
<td>1102</td>
</tr>
<tr>
<td>FP T4</td>
<td>2590</td>
<td>2234</td>
<td>2394</td>
<td>3030</td>
<td>2808</td>
</tr>
<tr>
<td>Time (FP)</td>
<td>1432</td>
<td>1335</td>
<td>1487</td>
<td>1643</td>
<td>1706</td>
</tr>
<tr>
<td>Calibration Interval (Frames and Time)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N Cine Film</td>
<td>363</td>
<td>339</td>
<td>364</td>
<td>402</td>
<td>433</td>
</tr>
<tr>
<td>N Force Plate</td>
<td>358.1</td>
<td>333.8</td>
<td>371.7</td>
<td>410.8</td>
<td>426.5</td>
</tr>
<tr>
<td>Film Rate (Hz)</td>
<td>246.6</td>
<td>246.2</td>
<td>255.3</td>
<td>255.5</td>
<td>246.3</td>
</tr>
<tr>
<td>Error Check</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage Difference</td>
<td>(246.6 - 246.2) 0.15%</td>
<td></td>
<td></td>
<td>(255.5 - 255.3) 0.07%</td>
<td></td>
</tr>
</tbody>
</table>

NB. Subject CJP6 was tested immediately following subject 1 and therefore appeared on film roll #0. Subject DDA3 arrived after subjects GCG4 and AKS5 and therefore appeared on film roll #2. The filmed sequences for subjects RED2, DJS7 and MMK8 were obliterated during the film processing and hence a reduced data set had to be used for the combined film and force plate analyses.

It can be seen that the framing rate varied slightly from trial to trial, although for film roll #0 and roll #2, there appears to have been some consistency with the rate settling at around 246 Hz. The amount of variation between trials was within the anticipated range of 0.2%, with the different trials on film roll #0 and roll #1 being in agreement to 0.15% and the corresponding variation for the trials on film roll #1 being 0.07%. The frame rate for film roll #1 was higher than the nominal figure at approximately 255 Hz.

Having established the correct framing rates, a generalised cross validated quintic spline
procedure based on Woltring (1986) and implemented by Challis (1991) was used to convert the
data from its nominal framing rate and digitising interval to a common 250 Hz timebase. The
resulting output data contained 12 coordinate pairs per frame corresponding to the originally
digitised points. These were input to programme ZatWinCM (Appendix B5.9) which processed
the data into a form suitable for use in the inverse dynamic and quasi-static analyses. Only five
coordinate pairs were required, (metatarsal-phalangeal, ankle, knee, hip and "trunk"). The
"trunk" was defined in three ways, hip to HAT mass centre (HATcm), hip to shoulder and hip
the ear. Each trunk definition was calculated using the hip, shoulder, elbow, wrist and ear
coordinates with the W and Z inertia data sets. Toe and heel data points were used to generate
foot lengths and the two knee coordinates were reduced to one representing the intersection of
the shank and thigh segments. The HAT segment moment of inertia values for the two data sets
(Z and W) were also calculated within this program. Output from the program included sets of
coordinates representing the locations of the metatarsal-phalangeal, ankle, knee and hip and
shoulder markers, the coordinates of the segment mass centre locations for the whole body, foot,
shank, thigh and trunk and the angle of the foot, shank, thigh and trunk. In addition mean and
standard deviation values for segment moments of inertia for the whole body, foot, shank, thigh,
trunk, upper arm, lower arm & hand and HAT segments were output.

Segments Angles

Three additional angles were output from the ZatWinCM program, hip to HAT, hip to shoulder
and hip to ear. These were used in deciding on the most appropriate trunk segment definition to
use in the inverse dynamic analyses. A sample graph to illustrate the differences between the
three trunk angle definitions has been provided in Figure 5.4. Hip to HATcm is the ideal
definition of the trunk angle since any movement of the head or arms is accommodated in the
calculation of the location of HAT cm, but from Figure 5.4, it can be seen that the Hip_Shoulder
definition is almost identical to Hip_HATcm whereas Hip to Ear is less appropriate. The root
mean square differences (RMSD) and Pearson Product Moment correlations (r) between each
criterion trunk angle (HIP_HATcm) and the two estimated trunk angles (HIP_Shoulder and
HIP_Ear) have been presented in Appendix 5.3. The location of the HATcm depended on the
inertia data set and so values for Z and W have been presented. Also the nature of the activity
(CMJ, RBJ and LDG) varied and so the data for the three phases have been reported in separate
sections with the associated means and standard deviations. A summary of the overall means
and standard deviations for all the data have been presented in Table 5.11. The overall mean
score for all types of jump for all subjects indicated that the difference between the trunk angle
defined by the line joining the hip to the shoulder was 1.6° compared with 3.1° for the line
joining the hip to ear. These values are root mean square differences between the line joining
the hip and the HATcm using both segmental inertia data sets. All subjects followed this pattern
with the exception of GCG who in five out of the six comparisons demonstrated a larger
difference in the opposite direction. The correlation coefficients when similarly averaged indicated that the shape of the graphs over the complete jump phases were 0.9995 and 0.9803 respectively. The level of agreement between the different methods for defining the trunk angles only varied slightly over the three phases with the corresponding means being 1.56°, 1.63° and 1.57° respectively. The correlation coefficients indicated that the shape of the shoulder curves (hip to shoulder link) for the CMJ phase were almost identical to the criterion HATcm curves ($r=0.9999$).

Figure 5.4. Trunk angles: Hip_HATcm, Hip_Shoulder and Hip_Ear during Counter Movement Jump, Rebound Jump and Landing for subject AAC.

Root Mean Square Differences and Correlations between criterion trunk angles (Hip_HATcm) and approximated trunk angles (Hip_Shoulder and Hip_Ear) for subjects AAC, DDA, GCG, AKS and CJP have been reported in Appendix 5.3.
However, the corresponding correlation coefficients for the RBJ and LDG where $r=0.9993$. In the case of the "Ear" curves (hip to ear link), the correlation coefficients for the CMJ, RBJ and LDG phases were 0.9822, 0.9780 and 0.9805 respectively.

Table 5.11. Root mean Square Differences and Correlations between criterion trunk angles (Hip_HATcm) and approximated trunk angles (Hip_Shoulder and Hip_Ear).

<table>
<thead>
<tr>
<th>Subject</th>
<th>RMSD (°)</th>
<th>r</th>
<th>RMSD (°)</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Z)</td>
<td>(W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
</tr>
<tr>
<td>Mean</td>
<td>1.72</td>
<td>3.10</td>
<td>0.9998</td>
<td>0.9819</td>
</tr>
<tr>
<td>StDev</td>
<td>0.84</td>
<td>0.60</td>
<td>0.0002</td>
<td>0.0112</td>
</tr>
<tr>
<td>RBJ</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
</tr>
<tr>
<td>Mean</td>
<td>1.9</td>
<td>2.92</td>
<td>0.9990</td>
<td>0.9771</td>
</tr>
<tr>
<td>StDev</td>
<td>0.62</td>
<td>1.92</td>
<td>0.0014</td>
<td>0.0316</td>
</tr>
<tr>
<td>LDG</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
</tr>
<tr>
<td>Mean</td>
<td>1.78</td>
<td>3.38</td>
<td>0.9991</td>
<td>0.9802</td>
</tr>
<tr>
<td>StDev</td>
<td>0.79</td>
<td>1.19</td>
<td>0.0009</td>
<td>0.0165</td>
</tr>
<tr>
<td>Marey</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
<td>Shld_Ear</td>
</tr>
<tr>
<td>MEAN</td>
<td>1.80</td>
<td>3.13</td>
<td>0.9993</td>
<td>0.9797</td>
</tr>
<tr>
<td>STDEV</td>
<td>0.70</td>
<td>1.27</td>
<td>0.0010</td>
<td>0.0201</td>
</tr>
</tbody>
</table>

Data on the five filmed trails AAC14, DDA33, GCG43, AKS53 and CJP63
Marey = Combination of all three phases of the jump
RMSD Shld = Root Mean Square Difference between the trunk angles defined by the Hip to HATcm and the Hip to Shoulder links
RMSD Ear = Root Mean Square Difference between the trunk angles defined by the Hip to HATcm and the Hip to Ear links
$r_{Shld}$ = Pearson Product Moment correlation coefficient between the trunk angles defined by the Hip to HATcm and the Hip to Shoulder links
$r_{Ear}$ = Pearson Product Moment correlation coefficient between the trunk angles defined by the Hip to HATcm and the Hip to Ear links

It would therefore appear that the line joining the hip to the shoulder is a better indicator of trunk angle than the line joining the hip to the ear and indicates that small movements of the head during the jumping activity contributed to the variations in the link angle which were not representative of the motion of the trunk as a whole. For this reason it was decided that the trunk should be defined either by the hip to HAT cm or hip to shoulder link and not by the hip to ear link. Examination of the variation in neck angle (i.e. the orientation of the line joining the shoulder to the ear) throughout each phase of the jump for the five digitised trials can be seen in Figure 5.5. The neck angle at the start of the CMJ was defined as zero. Each phase for each subject lasted varying amounts of time and so the data have been interpolated onto a percentage.
Figure 5.5. Neck orientation angles plotted against percentage of CMJ, RBJ and LDG jump actions.

Individual trail plots of neck orientation angles plotted against percentage of the three jump phases for subjects AAC, DDA, GCG, AKS and CJP have been included in Appendix A5.4.
scale and averaged over all subjects with 0% representing the start and 100% the end of each action. Positive angles indicate neck flexion and negative angles neck extension. The data showed that the average variations in neck angle were less than 1° although individual subject values ranged up to 2.5° (Appendix 5.4). In the five jumps analysed, neck flexion appeared to accompany landing and neck extension takeoff. However, the angle changes were small and smooth in nature and were therefore not likely to make a major contribution to the overall jumping actions.

Digitising Rate

The effects of using differing digitising rates were evaluated by comparing the output data files following the GCVQS procedure on the data digitised every frame with those generated using input files in which every other and every fifth frame had been digitised. The three phases of the filmed sequences for subject AAC were digitised every frame to produce three files on a nominal 250 Hz timebase. Two smaller data sets for each of these files were produced by selecting every other frame and every fifth frame (ie. on a nominal 125 Hz and a nominal 50 Hz timebase respectively). These files were input to the spline routine with a common 250 Hz output timebase. The GCVQS procedure interpolated, smoothed and differentiated the data to produce position, velocity and acceleration data files for each digitised point for each of the three phases of the jumping action. For the first takeoff sequence (CMJ), the differences between digitising every frame and every other frame were found to be minimal for horizontal and vertical position data (RMSD = 0.001 m). When every 5th frame was digitised the differences from the original data set increased to 0.002 m. The corresponding RMSD values for horizontal and vertical velocities were less than 0.1 m.s⁻¹ when every second frame was digitised and 0.14 m.s⁻¹ when data for every fifth frame were used. The equivalent RMSD acceleration values were 1.5 m.s⁻² and 4.0 m.s⁻² when every second and every fifth frame was used. The exception for the acceleration data was for the data associated with the toe marker which demonstrated extremely high horizontal values (43 m.s⁻² and 53 m.s⁻²) for every 2nd and every 5th frame respectively. The GCVQS position RMSD values have been summarised in Table 5.12. The toe marker was difficult to identify when digitising and therefore the toe data points and the associated derivative values were eliminated from all but one of the subsequent analyses. The exception being the position data which was used in the inertia data calculations for the 'Z' data set. Mean values of foot length were used over all frames and so the effects of the toe marker errors were minimised.

The acceleration RMSD values were consistently larger for the lower limb markers when using data collected every 5th frame rather than every 2nd frame and so when impacts were being digitised, where the accelerations were large and changing rapidly, every second frame was
digitised. For the actions where the body was moving relatively smoothly, every 5th frame only was digitised. Although the 250 Hz framing rate was beneficial in identifying takeoff and landing frames and for improving synchronisation with the force data, digitising every frame (equivalent to sampling at a frequency of 250 Hz) was found to be unnecessary.

Table 5.12. Root Mean Square Differences in position when digitising every frame compared with digitising every 2nd and 5th frame for subject AAC141 (m).

<table>
<thead>
<tr>
<th>Point</th>
<th>RMSDx2</th>
<th>RMSDy2</th>
<th>RMSDx5</th>
<th>RMSDy5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>M-P</td>
<td>0.003</td>
<td>0.001</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>Heel</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Ankle</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Knee1</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Knee2</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Hip</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Icrst</td>
<td>0.001</td>
<td>0.003</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>Wrist</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
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<td>0.001</td>
<td>0.001</td>
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<tr>
<td>Mean</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Filtering parameters

Initially the force and film data had to be synchronised. Five cinefilm frames had been digitised at the beginning and end of each phase of the Marey jump, but as these had been digitised at different frame intervals and with the film running at slightly varying speeds. It was necessary to align the new interpolated film data sets with the force plate data using real time events. The key times identified from the force plate data were used to ensure that the instants of takeoff and landing were accurately located. Force data were output at 250 Hz (ie. every tenth force reading) and matched with the cinefilm frames. The vertical locations of the whole body mass centre were then calculated for each inertia data set (Z and W) throughout each phase of the Marey jump. Prior to filtering using a Butterworth routine, the mass centre location data were padded. At the start of the CMJ and the end of the LDG phases the initial and final locations of the subject's mass centre was repeated to create 50 additional data points. After takeoff and prior to landing the equations of constant acceleration were used to generate additional mass centre locations during the projectile part of the motion. Each phase had sufficient extra data
points added to ensure that there were 50 additional points before and 50 additional points after the central part of the action. The data were then filtered (Butterworth) and differentiated using the second order direct difference procedures outlined by Miller and Nelson (1973) and Challis et al. (1991). The padded data points were clipped so that any distortions due to "end effects" were minimised. The resulting mass centre acceleration data sets were compared with the directly measured ground reaction force data which had been offset to body weight and divided by subject mass to produce criterion acceleration time data. The software was designed to iterate towards a minimum root mean square difference between the criterion and the filtered and differentiated acceleration time curves by systematically varying the Butterworth cutoff frequency and reporting the optimum cutoff frequency for each subject for each phase of each trial. The resulting cutoff frequencies for the vertical motion of the mass centre for each of the subjects for each phase of the filmed jump trials have been reported in Table 5.13. A similar procedure was conducted on the horizontal acceleration data but without the offset for body weight.

Table 5.13. Cutoff frequency ($f_c$) determined by minimum RMSD between acceleration of mass centre and criterion acceleration derived from vertical ground reaction force data.

<table>
<thead>
<tr>
<th>Subject</th>
<th>CMJ (Hz)</th>
<th>RBJ (Hz)</th>
<th>LDG (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC14</td>
<td>3.80</td>
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</tr>
<tr>
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</tr>
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<td>5.05</td>
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<td>4.57</td>
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</tr>
<tr>
<td>CJP63</td>
<td>10.40</td>
<td>5.81</td>
<td>4.76</td>
</tr>
</tbody>
</table>

In the RBJ and the LDG phases an impact was present and so a higher cutoff frequency would have been expected. However, more severe smoothing appeared to have been required to reduce the overall RMSD. Clearly, this highlighted the fact that over smoothing was necessary to ensure that the majority of the acceleration of each subject's mass centre motion was close to the active phase of the criterion data for the landing rather than to the transient in the first few milliseconds. The high frequency components within the transient could not be detected faithfully from the film but should be expected appear in the Fourier analyses of the force traces. The range in cutoff frequencies for the CMJ phase of the Marey jump was 7.75 Hz, whereas for the rebound and landing phases the range was 3 Hz and 2 Hz respectively. In the CMJ phase there appeared to be two distinct types of takeoff, one with a low frequency cutoff around 4 Hz for three subjects and one about 11 Hz for the remaining two subjects. In all cases the relatively low cutoff frequencies determined using the RMSD procedure were customised to the motion of the whole body mass centre and were therefore not necessarily appropriate for filtering the individual landmark coordinates. Filtering was necessary to reduce the unwanted effects of
noise amplification during differentiation but the range of cutoff frequencies required to accommodate the metatarsal-phalangeal impact with the force plate and the much smoother motion of the hip meant that GCVQS procedures were more effective for dealing with the raw digitised data. The Butterworth routine with the cutoff frequencies reported in Table 5.13 were used to investigate the effects of data smoothing on the inverse dynamic analyses in section 5.3.5.

5.3.3 Jump Height - flight time and integration

Analysis of Variance with repeated measures on one factor (ANOVAR1) was used to compare jump heights determined for takeoffs from counter movement and rebound jumps. Jump heights were calculated from flight times (JHf), from integrated vertical force time histories (JHt) and from integrated vertical force time histories with an integration correction factor (JHic). Differences between calculation methods and jump order were examined. Three separate ANOVAR1 calculations were performed to investigate whether the method of calculation used to determine jump height influenced the outcome. Initially the jump height values based on flight time were considered (Table 5.14a). No overall differences were found between the height attained whether the jump was performed following a counter movement or a rebound. A significant difference (p<0.01) was found between the trial means. That is, of the six means arising from the repeated jumps by the eight subjects, at least one mean was significantly different to the others. A post hoc Tukey test revealed that means four and one were different (p<0.01), and means one and six were different (p<0.05). When jump heights were calculated from takeoff velocity determined by integration whether with or without a correction factor (Tables 5.14b and 5.14c) no differences were observed in either factor or for the interactions.

There was a possibility that the calculation method used to determine the takeoff velocities, and hence jump heights, had an effect and so a two way ANOVA with repeated measures on both factors was performed for the CMJ and LDG phases of the Marey jump sequences for the eight subjects. When flight time and integration without integration correction were compared there was a very large difference (p<0.01) in factor 1, the calculation method as shown in Table 5.15a. However, when the flight time data were compared with the integration method following correction there was no significant difference in the resulting means, Table 5.15b. This pattern was repeated from the landing phase analyses, although the difference between the flight time and integration means was smaller with an F value about half that for the takeoff phase and significant at the p<0.05 level, Table 5.15c. Trial order did not result in any differences in the trial means for the takeoff phase.

For the landing phase, whether an integration correction was made or not, there were trial order differences (p<0.05) (Table 5.15c and d). Post hoc Tukey tests (Table 5.15Tc and 5.15Td) revealed differences between means three and six for the time v integration comparison and
Table 5.14. Comparison of jump heights attained using CMJ and RBJ takeoffs for eight subjects executing six repeated trials and three different calculation procedures.

a) Calculation by time of flight (JH_t)

ANOVA Summary Table

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b) Calculation by Integration (JH)

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c) Calculation by Integration with Constant correction (JH_{ic})

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In each section of the table, the rows are listed in the order:
Jump Type, Trial Number, Interaction followed by
Between Subjects Error, Within Subjects Error

d) Tukey Table for significant (p<0.01) differences observed in table 5.14a.

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<tbody>
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<td>5</td>
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J1 ** U2 *
M3
P4

** = p<0.01
* = p<0.05
Table 5.15. Comparison of Takeoff and Landing actions for eight subjects executing six repeated trials and three different calculation procedures.

a) CMJ Time/Integration for repeated trials

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b) CMJ Time/IntegrationC for repeated trials

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c) LDG Time/Integration for repeated trials

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d) LDG Time/IntegrationC for repeated trials

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In each section of the table, the rows are listed in the order: Calculation Method, Trial Number, Interaction followed by Calculation Method Subjects Errors, Trial order Subjects Errors and Interaction Subjects Errors

Tukey Tables (Tc & Td) corresponding to Tables 5.15c & d.

Tc. Landing (time/I, R)  

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Td. Landing (time/IC, R)

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</tr>
<tr>
<td>5</td>
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*= p<0.05
between means one and six for the time v integration with integration correction. Interaction effects were not significant in any of the analyses.

The first of the questions under examination in this chapter asked in what ways the takeoff actions following a counter movement and a rebound varied. No differences were found between jump heights following counter movement or rebound jump takeoffs. It is questionable whether the subjects were able to make a maximal effort in the CMJ takeoff, knowing that they had to retain sufficient control to be able to perform an immediate rebound jump and controlled landing. In Chapter 3, a series of counter movement jumps were analysed in which a controlled landing was required but without the requirement to perform the rebound jump. It could be assumed therefore that they were making the maximal effort to jump as high as possible. The subjects in the two different series were different, but the requirement to perform maximally was the same. Therefore, if there were no differences between the mean performances under the two conditions it could be assumed that the Marey rebounding requirement had not had a limiting effect on the performance of the CMJ takeoff. A 't' test was used to compare the takeoff velocities derived from integration. Since the series 1 (Chapter 3) data had not used an integration correction factor, the non corrected integration data from Chapter 5 were used in the comparisons. The two data sets were different with data from a total of 43 trials in series 1 (22 subjects performing 2 trials each) and 48 trials in series 2 (8 subjects performing 6 trials each) were available for comparison. If the overall mean scores were compared, there was a significant difference between the two ($t = 3.71, p<0.01$). However, if the first trials for the 8 subjects in series 2 were compared with the first 8 trials in series 1 there was no difference ($t = 1.70$). If the second series of 8 trials in series 2 was compared with the second series in series 1, again there were no differences ($t = 1.03$). The ages of the subjects in the first series was greater than that in the second series (28.8 ± 8.9 years compared with 24.3 ± 1.5 years). When the trials for the oldest three subjects were removed from series 1, and the 't' test repeated, there were no differences between the group means ($t = 2.57$). Without controlling the number of trials for matched subject samples it is impossible to say whether the need to perform a rebound, rather than a landing, influenced the takeoff commitment on the part of the subjects. However, the mean velocity at takeoff for series 1, although not significantly different from the mean velocity for series 2, was lower for all subsets (Table 5.16.) and indicates that the subjects were not inhibited by the need to perform the rebound takeoff.

The data from Chapter 3 for the drop jumps was also used in this section to compare with the rebound jump performances. Of the six drop heights used in Chapter 3, the 0.30 m drop height corresponded to the mean jump height for the first phase of the Marey jump (0.323 m). That is, when subjects landed for the rebound jump, they were effectively dropping from about 0.30 m above the force plate and so were performing a jump equivalent to a drop jump.
Table 5.16. Mean and standard deviation takeoff velocities for Series 1 (Chapter 3) and Series 2 (Chapter 5) Counter Movement Jumps.

<table>
<thead>
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<th>Series 2 (Chapter 5 Data)</th>
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</thead>
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<tr>
<td><strong>N</strong></td>
<td><strong>Mean</strong></td>
</tr>
<tr>
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</tr>
<tr>
<td>37</td>
<td>2.32</td>
</tr>
<tr>
<td>22,1</td>
<td>2.26</td>
</tr>
</tbody>
</table>
| 8,1 | 2.30 | 0.16 | [Subscripts 1,2= jump trial number]

The jump heights achieved following the rebound phase of the Marey trials were compared with the results obtained for the drop jumps from 0.30 m. There were similar discrepancies in the number of trials between the two series and so the first trials for the Marey rebound phase (n=8) were compared with the first trials for the drop jumps (n=6). A 't' value of 3.17 was less than the value of 3.77 (p<0.01) for the difference to be significant. The first trial drop jump data were also compared with the other five rebound trials and non were significantly different at the 1% level. When the significance level was reduced to p=0.05, the first three trials were different but trials 4, 5 and 6 were not.

In summary, two way analysis of variance with repeated measures on the factor of jump order was used to examine the relationship between jump height following a counter movement jump and a rebound jump. Irrespective of the calculation methods chosen, flight time, integration or integration with a constant correction, no differences were found. When the jump heights were calculated from the flight times, jump order did not appear to have any effect. Out of the 15 possible mean comparisons, two were found to be significantly different. A two way analysis of variance with repeated measures on calculation method and jump order was used to investigate the differences between CMJ takeoffs and LDG landings. It was found that integration with constant correction was necessary to ensure a similar result. If the constant correction was not applied, differences for the CMJ means (p<0.01) and the LDG means (p<0.05) were observed. Trial order did not have any effect in the counter movement jumps, but did produce a small difference in one pair of means for each of the two integration processes in comparison with the flight time data. There is no evidence to suggest that the subjects held back or were inhibited in the performance of a maximal effort CMJ by the requirement to perform the rebound jump on landing. It would appear that, for a data sample rate of 2.5kHz, using any of the three chosen methods for calculating jump or rebound height, for CMJ and RBJ trials, was acceptable and that takeoff (CMJ) and landing (LDG) parameters could be calculated using integration methods. In the latter case the integration process was best when performed in reverse, that is beginning with the subject stationary at the end of the exercise and summing backwards towards landing two (LDG2).
5.3.4 Frequency content

The analysis procedures used in this section were selected to identify differences in the fundamental nature of the movements and to provide information for the data filtering procedures used in the force and film analyses. The frequency content of the takeoff (CMJ), rebound (RBJ) and landing (LDG) actions were determined using FFT analyses of the force plate data for eight subjects. A total of 144 Power Spectral Density (PSD) plots were generated with each subject performing six "Marey" jumps comprising three phases. Mean power spectra for each subject for each phase of the jump were generated using programme (FFT_nrgM, Appendix B5.7) and output for graphical plotting using programme (MeanPwr, Appendix B5.8). This procedure used the ADDPR and DLOGPWR commands from the CED1401 library to combine the six separate FFT analyses to produce log linear graphs of amplitude (dB) against frequency (Hz) representative of the six trials. In addition the individual PSD plots for the five individual trials which were filmed were also plotted. Figure 5.6 shows a summary of the mean and individual power spectral density plots for subject number 1 (AAC). Equivalent data for subjects 2-8 are contained in Appendix A5.12. The four graphs on the left hand side of Figure 5.6a show mean data and the four on the right hand side (Figure 5.6b) the data for the filmed trial, in this case trial #4. Reading from top to bottom, the graphs present data for the counter movement (CMJ) phase of the Marey jump, followed by the rebound (RBJ) and landing (LDG). The final pair of graphs at the bottom of Figure 5.6 summarise the three phases of the jump. On each of the three phases of the jump the dotted vertical line marks the frequency up to which 99% of the signal energy was contained. The bandwidths of the counter movement and the landing phases are narrower than for the rebound phases. Typically for the counter movement phase of the action, frequencies up to about 125 Hz appear. In the individual trial (AAC4) the shape of the PSD plot is slightly different to the shape in the associated mean plot. However, the dotted vertical line indicates that in both cases very little signal energy was present above 10 Hz. This pattern was repeated for the landing phase. The graphs for the rebound phase were more varied. The individual trial contains many high frequency components and was noticeably different to its mean counterpart. The variation in the frequency profiles was minimal for the counter movement and landing phases, (Standard deviations of ±0.6 Hz and ±0.7 Hz respectively) for subject AAC, but for the rebound phase the standard deviation was ±7.2 Hz. This pattern was repeated for all but one of the subjects with the standard deviation being within approximately one harmonic for the CMJ phase. For the LDG phase of the jump the standard deviations ranged from about ½ to 5 times the first harmonic (1.22 Hz) compared with a range of from about 2-18 times the first harmonic for the rebound phase. These data have been summarised in Table 5.17.

The output data for the signal energy calculation has been summarised in Table 5.18. It shows the frequencies needed to contain 95%, 99% and 99.9% of the signal energy for each subject,
together with the mean and standard deviation values for each of the three phases of the jumping action. It can be seen that even though frequencies from DC up to 250 Hz were present, almost all of the signal energy was contained within the first 50 Hz. The overall mean values for all subjects for all trials for the CMJ, RBJ and LDG phases were approximately 4 Hz, 29 Hz and 8 Hz respectively (99% signal energy level).

Table 5.17. Means and standard deviations of frequencies (Hz) containing 99% of signal energy for each of eight subjects over 6 trials.

<table>
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<tr>
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<th>CMJ</th>
<th>RBJ</th>
<th>LDG</th>
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<td>Mean</td>
<td>StDev</td>
<td>Mean</td>
<td>StDev</td>
</tr>
<tr>
<td>AAC</td>
<td>3.26</td>
<td>0.63</td>
<td>12.82</td>
</tr>
<tr>
<td>RED</td>
<td>2.85</td>
<td>0.63</td>
<td>31.13</td>
</tr>
<tr>
<td>DDA</td>
<td>5.29</td>
<td>1.26</td>
<td>51.88</td>
</tr>
<tr>
<td>GCG</td>
<td>4.68</td>
<td>3.13</td>
<td>16.48</td>
</tr>
<tr>
<td>AKS</td>
<td>3.46</td>
<td>0.92</td>
<td>10.17</td>
</tr>
<tr>
<td>CJP</td>
<td>2.85</td>
<td>0.63</td>
<td>43.33</td>
</tr>
<tr>
<td>DJS</td>
<td>3.05</td>
<td>0.67</td>
<td>26.45</td>
</tr>
<tr>
<td>MMK</td>
<td>4.88</td>
<td>1.09</td>
<td>39.88</td>
</tr>
</tbody>
</table>

The resolution was 1.22 Hz per step since 2048 samples spanned all frequencies from DC to the Nyquist limit of 1250 Hz (half the sampling frequency of 2500 Hz). The lower half of the data array contained the frequency data of interest. As a result all frequencies have been reported as multiples of 1.22 Hz and some detail has therefore been lost. Inevitably some spectral smearing occurred as a consequence of the digital transform used. Windowing the force data with a raised cosine reduced this influence but would also have attenuated peak amplitudes in the frequency profiles.

There were clear differences between the frequencies required to contain 95%, 99% and 99.9% of the signal energy and between the three jumping phases. A two way ANOVA with repeated measures on both factors followed by Tukey tests was used to determine which of the differences between the relevant means were responsible for the significant 'F ratios. The differences between the the three phases of jumping were significant at the 1% level. Tukey tests revealed that only the differences between the rebound phase and the other two phases were significantly different and that the takeoff and landings were not different at either the 1% or the 5% levels of significance. The results of the ANOVA have been summarised in Table 5.19a and the associated Tukey results in Table 5.19b. The Tukey tests revealed that the differences in signal energies were found when comparing the 95% and 99% levels with the 99.9% value. There were no differences between the 95% and 99% signal energy profiles at either p<0.05 or p<0.01. To ensure that almost all the energy in the signal was faithfully recorded, frequencies in excess of 100Hz were required for the rebound phase of the jump for at least three of the subjects. This meant that the sampling frequency of 250 Hz for the filming
Figure 5.6a. AAC Mean PSD

Figure 5.6b. AAC4 PSD

Figure 5.6. Marey Jump Force Data Power spectral Density Plots for Subject AAC.
was justified. However, the additional information gained as a result of using this high sampling rate was not shown to add to the position, velocity or acceleration data quality. Reducing the digitising interval to every 5th frame (=50 Hz) was justifiable for the CMJ and the majority of the LDG phases since almost all (99%) or the signal energy was below 10 Hz. Every other frame of the rebound phase was digitised (=125 Hz) to ensure that the frequencies close to 30 Hz were not aliased.

The force data had been filtered and so the maximum frequency still within the data was 256 Hz, (0.1024 x 2500 Hz). To check that the filtering had not adversely influenced the force data signal energy conclusions, the ANOVA and Tukey analyses were also conducted on the FFT output of the unfiltered force data.

Table 5.18. FFT analyses of the Filtered Vertical Ground Reaction Force data for the three phases of the Marey Jump showing frequencies below which 95%, 99% and 99.9% of the signal energy was contained for the 8 subjects over 6 trials per subject.

(a) Mean data

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th></th>
<th>RBJ</th>
<th></th>
<th>LDG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95.0%</td>
<td>99.0%</td>
<td>99.9%</td>
<td>95.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>AAC</td>
<td>2.44</td>
<td>3.26</td>
<td>6.10</td>
<td>6.10</td>
<td>12.82</td>
</tr>
<tr>
<td>RED</td>
<td>2.44</td>
<td>2.85</td>
<td>6.31</td>
<td>8.95</td>
<td>31.13</td>
</tr>
<tr>
<td>DDA</td>
<td>3.66</td>
<td>5.29</td>
<td>9.97</td>
<td>24.62</td>
<td>51.88</td>
</tr>
<tr>
<td>GCG</td>
<td>2.85</td>
<td>4.68</td>
<td>10.38</td>
<td>5.70</td>
<td>16.48</td>
</tr>
<tr>
<td>AKS</td>
<td>2.24</td>
<td>3.46</td>
<td>7.53</td>
<td>7.93</td>
<td>10.17</td>
</tr>
<tr>
<td>CJP</td>
<td>2.64</td>
<td>2.85</td>
<td>6.31</td>
<td>14.04</td>
<td>43.33</td>
</tr>
<tr>
<td>DJS</td>
<td>2.44</td>
<td>3.10</td>
<td>6.31</td>
<td>9.97</td>
<td>26.40</td>
</tr>
<tr>
<td>MMK</td>
<td>2.44</td>
<td>4.90</td>
<td>7.12</td>
<td>15.26</td>
<td>39.90</td>
</tr>
<tr>
<td>Mean</td>
<td>2.64</td>
<td>3.80</td>
<td>7.50</td>
<td>11.57</td>
<td>29.01</td>
</tr>
<tr>
<td>St.Dev</td>
<td>0.45</td>
<td>0.99</td>
<td>1.72</td>
<td>6.29</td>
<td>15.27</td>
</tr>
</tbody>
</table>

(b) Individual Film Trial Data

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th></th>
<th>RBJ</th>
<th></th>
<th>LDG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95.0%</td>
<td>99.0%</td>
<td>99.9%</td>
<td>95.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>AAC3</td>
<td>2.44</td>
<td>2.44</td>
<td>6.10</td>
<td>7.32</td>
<td>26.86</td>
</tr>
<tr>
<td>RED3</td>
<td>2.44</td>
<td>2.44</td>
<td>6.10</td>
<td>8.54</td>
<td>24.41</td>
</tr>
<tr>
<td>DDA3</td>
<td>3.66</td>
<td>7.32</td>
<td>9.77</td>
<td>10.99</td>
<td>35.40</td>
</tr>
<tr>
<td>GCG3</td>
<td>3.66</td>
<td>7.32</td>
<td>15.87</td>
<td>8.54</td>
<td>30.52</td>
</tr>
<tr>
<td>AKS3</td>
<td>2.44</td>
<td>2.44</td>
<td>8.54</td>
<td>9.77</td>
<td>9.77</td>
</tr>
<tr>
<td>CJP3</td>
<td>2.44</td>
<td>2.44</td>
<td>3.66</td>
<td>6.10</td>
<td>18.31</td>
</tr>
<tr>
<td>DJS4</td>
<td>2.44</td>
<td>3.66</td>
<td>6.10</td>
<td>7.32</td>
<td>9.77</td>
</tr>
<tr>
<td>MMK4</td>
<td>2.44</td>
<td>4.88</td>
<td>8.54</td>
<td>12.21</td>
<td>28.08</td>
</tr>
<tr>
<td>Mean</td>
<td>2.75</td>
<td>4.12</td>
<td>8.09</td>
<td>8.85</td>
<td>22.89</td>
</tr>
<tr>
<td>St.Dev</td>
<td>0.56</td>
<td>2.16</td>
<td>3.69</td>
<td>2.04</td>
<td>9.45</td>
</tr>
</tbody>
</table>

The results were very similar to those obtained with the filtered data. Not surprisingly a wider range of frequencies was required to encompass more of the signal energy, however at the 95% and 99% levels for CMJ and LDG, the key frequencies were still below 10 Hz. (A summary of the values for the unfiltered force data are presented in Appendix A5.6).
Table 5.19a. ANOVA summary table of comparisons between jump phases and percentages of signal energy from FFT analysis of Marey Jumping actions for 8 subjects and 6 trials per subject.

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>df</th>
<th>Var</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump Phase</td>
<td>15282</td>
<td>2</td>
<td>7641</td>
<td>28.79 (p&lt;0.01)</td>
</tr>
<tr>
<td>Percentages</td>
<td>12558</td>
<td>2</td>
<td>6279</td>
<td>50.13 (p&lt;0.01)</td>
</tr>
<tr>
<td>Interaction</td>
<td>7849</td>
<td>4</td>
<td>1962</td>
<td>20.95 (p&lt;0.01)</td>
</tr>
<tr>
<td>Jump x subject</td>
<td>3715</td>
<td>14</td>
<td>265</td>
<td></td>
</tr>
<tr>
<td>Percent x subject</td>
<td>1754</td>
<td>14</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Interact x Subject</td>
<td>2623</td>
<td>28</td>
<td>94</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.19b. Tukey test analysis associated with the ANOVA summary in Table 5.19a.

<table>
<thead>
<tr>
<th>Jumping Phase</th>
<th>Mean Differences</th>
<th>Percentage Signal Mean Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T&lt;sub&gt;0.05&lt;/sub&gt; = 12.30, T&lt;sub&gt;0.01&lt;/sub&gt; = 16.26)</td>
<td>(T&lt;sub&gt;0.05&lt;/sub&gt; = 8.45, T&lt;sub&gt;0.01&lt;/sub&gt; = 11.17)</td>
<td></td>
</tr>
<tr>
<td>RBJ</td>
<td>34.18**</td>
<td>99%</td>
</tr>
<tr>
<td>LDG</td>
<td>8.19</td>
<td>99.9%</td>
</tr>
<tr>
<td>CMJ</td>
<td>25.99**</td>
<td>95%</td>
</tr>
<tr>
<td>RBJ</td>
<td>7.76</td>
<td>31.08**</td>
</tr>
<tr>
<td>(** = Significant at p&lt;0.01)</td>
<td>23.32**</td>
<td></td>
</tr>
</tbody>
</table>

In addition, a plot of the PSD plots for one subject (AAC) for the rebound phase of jump 4 has been presented in Figure 5.20. The unfiltered vertical force (Fz) data (Figure 5.20a) illustrates the frequency components arising from the resonances of the plate identified in Chapter 4 and subsequently removed with the use of the Bi-Linear filter with cutoff frequency at 256 Hz and displayed in the lower plot in Figure 5.20b.

It became clear that for the takeoff and landing phases of the jump, any filtering of cinefilm data, essential for obtaining derivatives, was unlikely to remove much of the signal whilst eliminating the majority of the noise. The data in Table 5.18a summarises the signal energy for the eight subjects at the 99% level for each of the three phases of the Marey jump. The cutoff frequency for all subjects were similar in the takeoff phase and therefore a common cutoff frequency was likely to be usable, but the landing phases needed more tuning. The rebound phases in particular were more varied and so subject specific filtering was likely to be needed.

The mean cutoff frequencies required for the three phases of the jump were approximately 4 Hz, 29 Hz and 8 Hz. These corresponded to harmonics of 2.5, 23.8 and 6.6 for the three phases of the Marey jump action. If the 95% level were used, the harmonics required were as low as 2.2, 9.5 and 2.7 respectively for the CMJ, RBJ and LDG phases.
Figure 5.7. PSD plot of Unfiltered and Filtered force plate data for the rebound phase of jump 4 for subject AAC.

A = Unfiltered Fz force data for subject AAC RBJ trial 4, 
B = Filtered Fz force data for subject AAC RBJ trial 4.
5.3.5 Inverse Dynamic Analysis

The primary purpose for conducting the inverse dynamic analyses was to answer the secondary questions,

(i) in what ways do the takeoff actions following a counter movement and a rebound vary?

(ii) in what ways do the landing actions preceding a rebound jump and a return to rest vary?

The Marey jump contains three phases each of which is either a takeoff (TO1), a landing (LDG2) or a combination of both (RBJ = LDG1 & TO2). To divide the CMJ, RBJ and LDG actions into takeoffs and landings the lowest point of the displacement of each subject's mass centre was taken as the boundary. Each takeoff and landing action was divided into downward and upward parts so that takeoff one (toff1) began from the lowest point of the squat in the counter movement jump and ended when ground contact was lost. Landing two (ldg2) began when the feet touched the force plate and ended when the lowest mass centre displacement of the LDG phase was reached. Landing one (ldg1) and takeoff two (tof2) were divided at the lowest mass centre displacement in the rebound jump phase. The durations of each phase have been reported in Table 5.20a. Tables 5.20b, 5.20c, 5.20d and 5.20e contain a summary of the corresponding squat depths (minimum mass centre height), stretch heights (height of the mass centre at force plate contact and takeoff), peak vertical forces at the lowest point of the squat and takeoff or landing mass centre velocities. Statistical 't' tests were used to compare the means of the six trials for each of the eight subjects so that toff1 was compared with tof2 and ldg1 was compared with ldg2. In Tables 5.20a, 5.20c and 5.20e there were four values for comparison. In Tables 5.20b and 5.20d there were three values since the depth of squat and the peak vertical force at the time of minimum squat for the rebound phase of the jump constituted ldg1 and tof2.

The time taken to land during a rebound was longer (p<0.01) than that required for landing prior to coming to rest (0.281 s and 0.238 s respectively). Although the overall difference between the time taken for toff1 was significantly shorter than that for tof2 (p<0.05), there was no consistent pattern between subjects with some taking more time and some taking less time for each action. There was no difference between the depth of squat in toff1 and tof2, but the depth of squat in the ldg2 was shallower than that for ldg1 (p<0.01). In contrast the stretch height in toff1 was lower than for tof2, indicating that the subjects were more fully extended following a rebound jump than a counter movement jump. The vertical forces (normalised to body weight) at the lowest point of the squat were progressively reduced throughout the jump sequence for all subjects except one (AAC). The largest forces were generated by the subjects at the lowest point of the squat during the CMJ (2.50 BW), followed by the RBJ (2.21 BW) and smallest in the LDG (1.83 BW). There were no significant differences between these forces in toff1 and tof2,
Table 5.20a. Mean durations of takeoffs and landings in the Marey Jump action.

<table>
<thead>
<tr>
<th>Subject</th>
<th>tof_1(s)</th>
<th>ldg_1(s)</th>
<th>tof_2(s)</th>
<th>ldg_2(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>0.253</td>
<td>0.212</td>
<td>0.228</td>
<td>0.205</td>
</tr>
<tr>
<td>RED</td>
<td>0.281</td>
<td>0.366</td>
<td>0.331</td>
<td>0.346</td>
</tr>
<tr>
<td>DDA</td>
<td>0.179</td>
<td>0.251</td>
<td>0.241</td>
<td>0.346</td>
</tr>
<tr>
<td>GCG</td>
<td>0.231</td>
<td>0.247</td>
<td>0.225</td>
<td>0.191</td>
</tr>
<tr>
<td>AKS</td>
<td>0.219</td>
<td>0.238</td>
<td>0.269</td>
<td>0.222</td>
</tr>
<tr>
<td>CJP</td>
<td>0.217</td>
<td>0.259</td>
<td>0.237</td>
<td>0.181</td>
</tr>
<tr>
<td>DJS</td>
<td>0.283</td>
<td>0.312</td>
<td>0.307</td>
<td>0.256</td>
</tr>
<tr>
<td>MMK</td>
<td>0.253</td>
<td>0.212</td>
<td>0.228</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Table 5.20b. Mean depth of squat for takeoffs and landings in the Marey Jump action.

<table>
<thead>
<tr>
<th>Subject</th>
<th>tof_1(m)</th>
<th>ldg_1(m)</th>
<th>tof_2(m)</th>
<th>ldg_2(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>-0.193</td>
<td>-0.140</td>
<td>-0.140</td>
<td>-0.088</td>
</tr>
<tr>
<td>RED</td>
<td>-0.342</td>
<td>-0.359</td>
<td>-0.359</td>
<td>-0.312</td>
</tr>
<tr>
<td>DDA</td>
<td>-0.140</td>
<td>-0.182</td>
<td>-0.182</td>
<td>-0.077</td>
</tr>
<tr>
<td>GCG</td>
<td>-0.253</td>
<td>-0.198</td>
<td>-0.198</td>
<td>-0.145</td>
</tr>
<tr>
<td>AKS</td>
<td>-0.291</td>
<td>-0.316</td>
<td>-0.316</td>
<td>-0.255</td>
</tr>
<tr>
<td>CJP</td>
<td>-0.249</td>
<td>-0.272</td>
<td>-0.272</td>
<td>-0.192</td>
</tr>
<tr>
<td>DJS</td>
<td>-0.216</td>
<td>-0.216</td>
<td>-0.216</td>
<td>-0.125</td>
</tr>
<tr>
<td>MMK</td>
<td>-0.282</td>
<td>-0.236</td>
<td>-0.236</td>
<td>-0.165</td>
</tr>
</tbody>
</table>

Table 5.20c. Mean stretch height for takeoffs and landings in the Marey Jump action.

<table>
<thead>
<tr>
<th>Subject</th>
<th>tof_1(m)</th>
<th>ldg_1(m)</th>
<th>tof_2(m)</th>
<th>ldg_2(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>0.167</td>
<td>0.138</td>
<td>0.196</td>
<td>0.132</td>
</tr>
<tr>
<td>RED</td>
<td>0.134</td>
<td>0.195</td>
<td>0.158</td>
<td>0.192</td>
</tr>
<tr>
<td>DDA</td>
<td>0.122</td>
<td>0.103</td>
<td>0.142</td>
<td>0.114</td>
</tr>
<tr>
<td>GCG</td>
<td>0.152</td>
<td>0.127</td>
<td>0.181</td>
<td>0.130</td>
</tr>
<tr>
<td>AKS</td>
<td>0.153</td>
<td>0.100</td>
<td>0.163</td>
<td>0.113</td>
</tr>
<tr>
<td>CJP</td>
<td>0.134</td>
<td>0.093</td>
<td>0.146</td>
<td>0.106</td>
</tr>
<tr>
<td>DJS</td>
<td>0.135</td>
<td>0.146</td>
<td>0.144</td>
<td>0.090</td>
</tr>
<tr>
<td>MMK</td>
<td>0.228</td>
<td>0.285</td>
<td>0.267</td>
<td>0.244</td>
</tr>
</tbody>
</table>

Table 5.20d. Mean vertical force at minimum squat position for takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>tof_1(BW)</th>
<th>ldg_1(BW)</th>
<th>tof_2(BW)</th>
<th>ldg_2(BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>1.979</td>
<td>2.439</td>
<td>2.439</td>
<td>1.610</td>
</tr>
<tr>
<td>RED</td>
<td>2.498</td>
<td>2.067</td>
<td>2.067</td>
<td>1.834</td>
</tr>
<tr>
<td>DDA</td>
<td>2.827</td>
<td>1.960</td>
<td>1.960</td>
<td>1.781</td>
</tr>
<tr>
<td>GCG</td>
<td>2.791</td>
<td>2.486</td>
<td>2.486</td>
<td>2.069</td>
</tr>
<tr>
<td>AKS</td>
<td>1.886</td>
<td>1.671</td>
<td>1.671</td>
<td>1.548</td>
</tr>
<tr>
<td>CJP</td>
<td>2.701</td>
<td>2.246</td>
<td>2.246</td>
<td>1.796</td>
</tr>
<tr>
<td>DJS</td>
<td>2.448</td>
<td>2.422</td>
<td>2.422</td>
<td>1.897</td>
</tr>
<tr>
<td>MMK</td>
<td>2.870</td>
<td>2.370</td>
<td>2.370</td>
<td>2.113</td>
</tr>
</tbody>
</table>

BW = Multiples of Body Weight

Table 5.20e. Mean vertical velocity for takeoffs and landings in the Marey Jump action.

<table>
<thead>
<tr>
<th>Subject</th>
<th>tof_1(m.s^-1)</th>
<th>ldg_1(m.s^-1)</th>
<th>tof_2(m.s^-1)</th>
<th>ldg_2(m.s^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>2.337</td>
<td>-2.438</td>
<td>2.214</td>
<td>-2.467</td>
</tr>
<tr>
<td>RED</td>
<td>2.623</td>
<td>-2.270</td>
<td>2.592</td>
<td>-2.560</td>
</tr>
<tr>
<td>DDA</td>
<td>2.018</td>
<td>-2.046</td>
<td>2.002</td>
<td>-2.070</td>
</tr>
<tr>
<td>GCG</td>
<td>2.520</td>
<td>-2.562</td>
<td>2.343</td>
<td>-2.499</td>
</tr>
<tr>
<td>AKS</td>
<td>2.054</td>
<td>-2.239</td>
<td>2.003</td>
<td>-2.180</td>
</tr>
<tr>
<td>CJP</td>
<td>2.750</td>
<td>-2.818</td>
<td>2.619</td>
<td>-2.689</td>
</tr>
<tr>
<td>DJS</td>
<td>2.350</td>
<td>-2.221</td>
<td>2.232</td>
<td>-2.385</td>
</tr>
<tr>
<td>MMK</td>
<td>2.258</td>
<td>-2.000</td>
<td>2.006</td>
<td>-2.123</td>
</tr>
</tbody>
</table>
but those for ldg\textsubscript{1} were greater than those for ldg\textsubscript{2} (p<0.01). For all subjects the tof\textsubscript{1} velocity was higher than tof\textsubscript{2} velocity (p<0.01). However the total heights achieved were not different. This matched with the observation that the stretch height at tof\textsubscript{2} was greater than the stretch height for tof\textsubscript{1}. It would appear therefore that all subjects lost contact with the ground in tof\textsubscript{1} earlier and hence with a higher velocity than in tof\textsubscript{2}. This combination was reversed in tof\textsubscript{2}, but the net effect was a jump of equal height for both actions. The equivalent data for the individual filmed trials have been presented in Tables 5.21a to 5.21e. The pattern of data for the filmed trials was very similar to that for the mean data in Tables 5.20a to 5.20e. For example, the peak forces at the deepest point of the squat followed exactly the same pattern as those for the group data. The stretch heights of the mass centre at takeoff and landing, also followed very closely, with subject CJP exhibiting a slight variation. The general pattern of decreasing depth of squat with duration of the action and the duration of each phase although not exactly in line with the mean values, followed the same overall pattern. It was therefore reasonable to treat the filmed trial as a typical and therefore representative trial. In addition, since considerably more data was available for the filmed trials, additional comparisons could be examined. Joint angles and relative joint angular velocities at takeoffs and landings have been summarised in Tables 5.22a to 5.22d. The angles at the ankle, knee and hip joints were compared for the two takeoffs and landings. The three joint angles were averaged to represent overall joint extension and the differences between the mean extension angles for the two takeoffs (ΔT°) were calculated, as shown in the final column in Table 5.22a. It can be seen that there were variations between the five subjects. Subject AAC was more extended in tof\textsubscript{1} than in tof\textsubscript{2}. Subject DDA was equally extended in both takeoffs and the other three subjects were more extended in the rebound jump takeoff than the counter movement jump takeoff. The mean differences ranged from -5° to +20°, with a mean of 8°. In Table 5.22b, the mean extension prior to ldg\textsubscript{2} was almost the same as for ldg\textsubscript{1}. Again there were variations, with subject GCG being 7° per joint more extended prior to the second landing than for the first landing. However, subject CJP was 4° per joint more extended prior to ldg\textsubscript{1} than for ldg\textsubscript{2}. Although only five values were available, a 't' test was conducted which supported the observation that the leg extensions for the takeoffs were different (p<0.025), but the leg extensions for the landings were not different. A similar comparison was made between the takeoff and landing relative angular velocities of the ankle, knee and hip joints and have been reported in Tables 5.22c and 5.22d. The mean takeoff relative angular velocities for all subjects were greater in tof\textsubscript{2} than in tof\textsubscript{1}. The values ranged from just of 50°.s\textsuperscript{-1} to just over 300°.s\textsuperscript{-1} with a mean of 171°.s\textsuperscript{-1}. For landing the variation was more marked. Subject AKS had a positive difference indicating that his legs were extending more rapidly prior to ldg\textsubscript{2} than ldg\textsubscript{1}, but this was the exception. Values ranged from -95°.s\textsuperscript{-1} to +70°.s\textsuperscript{-1} with a mean of -36°.s\textsuperscript{-1}. Statistical 't' tests supported the observation that takeoff mean angular velocities were greater for tof\textsubscript{2} than tof\textsubscript{1} (p<0.01), but that the differences in landing mean angular velocities were not different statistically.
Table 5.21a. Durations of takeoffs and landings in the filmed takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$t_{of1}$ (s)</th>
<th>$l_{dg1}$ (s)</th>
<th>$t_{of2}$ (s)</th>
<th>$l_{dg2}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>0.244</td>
<td>0.196</td>
<td>0.212</td>
<td>0.152</td>
</tr>
<tr>
<td>DDA</td>
<td>0.184</td>
<td>0.268</td>
<td>0.236</td>
<td>0.172</td>
</tr>
<tr>
<td>GCG</td>
<td>0.216</td>
<td>0.248</td>
<td>0.232</td>
<td>0.228</td>
</tr>
<tr>
<td>AKS</td>
<td>0.324</td>
<td>0.360</td>
<td>0.388</td>
<td>0.332</td>
</tr>
<tr>
<td>CJP</td>
<td>0.224</td>
<td>0.280</td>
<td>0.352</td>
<td>0.244</td>
</tr>
</tbody>
</table>

Table 5.21b. Depth of squat for takeoffs and landings in the filmed takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$t_{of1}$ (m)</th>
<th>$l_{dg1}$ (m)</th>
<th>$t_{of2}$ (m)</th>
<th>$l_{dg2}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>-0.230</td>
<td>-0.188</td>
<td>-0.188</td>
<td>-0.093</td>
</tr>
<tr>
<td>DDA</td>
<td>-0.146</td>
<td>-0.176</td>
<td>-0.176</td>
<td>-0.068</td>
</tr>
<tr>
<td>GCG</td>
<td>-0.236</td>
<td>-0.214</td>
<td>-0.214</td>
<td>-0.161</td>
</tr>
<tr>
<td>AKS</td>
<td>-0.271</td>
<td>-0.285</td>
<td>-0.285</td>
<td>-0.289</td>
</tr>
<tr>
<td>CJP</td>
<td>-0.273</td>
<td>-0.328</td>
<td>-0.328</td>
<td>-0.208</td>
</tr>
</tbody>
</table>

Table 5.21c. Stretch height for takeoffs and landings in the filmed takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$t_{of1}$ (m)</th>
<th>$l_{dg1}$ (m)</th>
<th>$t_{of2}$ (m)</th>
<th>$l_{dg2}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>0.115</td>
<td>0.081</td>
<td>0.133</td>
<td>0.093</td>
</tr>
<tr>
<td>DDA</td>
<td>0.126</td>
<td>0.111</td>
<td>0.136</td>
<td>0.100</td>
</tr>
<tr>
<td>GCG</td>
<td>0.148</td>
<td>0.130</td>
<td>0.154</td>
<td>0.128</td>
</tr>
<tr>
<td>AKS</td>
<td>0.175</td>
<td>0.132</td>
<td>0.180</td>
<td>0.117</td>
</tr>
<tr>
<td>CJP</td>
<td>0.113</td>
<td>0.068</td>
<td>0.110</td>
<td>0.090</td>
</tr>
</tbody>
</table>

Table 5.21d. Vertical force at squat position for the filmed takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$t_{of1}$ (BW)</th>
<th>$l_{dg1}$ (BW)</th>
<th>$t_{of2}$ (BW)</th>
<th>$l_{dg2}$ (BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>1.998</td>
<td>2.358</td>
<td>2.358</td>
<td>1.701</td>
</tr>
<tr>
<td>DDA</td>
<td>2.747</td>
<td>1.959</td>
<td>1.959</td>
<td>1.860</td>
</tr>
<tr>
<td>GCG</td>
<td>2.923</td>
<td>2.113</td>
<td>2.113</td>
<td>1.667</td>
</tr>
<tr>
<td>AKS</td>
<td>1.948</td>
<td>1.741</td>
<td>1.741</td>
<td>1.532</td>
</tr>
<tr>
<td>CJP</td>
<td>2.588</td>
<td>1.598</td>
<td>1.598</td>
<td>1.532</td>
</tr>
</tbody>
</table>

BW = Multiples of Body Weight

Table 5.21e. Vertical velocity of mass centre for the filmed takeoffs and landings.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$t_{of1}$ (m.s⁻¹)</th>
<th>$l_{dg1}$ (m.s⁻¹)</th>
<th>$t_{of2}$ (m.s⁻¹)</th>
<th>$l_{dg2}$ (m.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>2.438</td>
<td>-2.520</td>
<td>2.321</td>
<td>-2.440</td>
</tr>
<tr>
<td>DDA</td>
<td>2.059</td>
<td>-2.084</td>
<td>1.887</td>
<td>-2.022</td>
</tr>
<tr>
<td>GCG</td>
<td>2.516</td>
<td>-2.523</td>
<td>2.343</td>
<td>-2.386</td>
</tr>
<tr>
<td>AKS</td>
<td>2.095</td>
<td>-2.234</td>
<td>2.027</td>
<td>-2.263</td>
</tr>
<tr>
<td>CJP</td>
<td>2.743</td>
<td>-2.764</td>
<td>2.469</td>
<td>-2.412</td>
</tr>
</tbody>
</table>

Data in Tables 5.21a to 5.21e were based on the filmed trial for each subject.
Table 5.22a. Ankle, Knee and Hip angles at takeoffs 1 and 2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Takeoff 1 Ankle (°)</th>
<th>Knee (°)</th>
<th>Hip (°)</th>
<th>Takeoff 2 Ankle (°)</th>
<th>Knee (°)</th>
<th>Hip (°)</th>
<th>ΔT (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>158</td>
<td>183</td>
<td>179</td>
<td>156</td>
<td>179</td>
<td>171</td>
<td>-5</td>
</tr>
<tr>
<td>DDA</td>
<td>152</td>
<td>180</td>
<td>168</td>
<td>152</td>
<td>180</td>
<td>165</td>
<td>-1</td>
</tr>
<tr>
<td>GCG</td>
<td>135</td>
<td>144</td>
<td>143</td>
<td>155</td>
<td>167</td>
<td>160</td>
<td>+20</td>
</tr>
<tr>
<td>AKS</td>
<td>133</td>
<td>137</td>
<td>150</td>
<td>155</td>
<td>158</td>
<td>163</td>
<td>+19</td>
</tr>
<tr>
<td>CJP</td>
<td>151</td>
<td>176</td>
<td>159</td>
<td>156</td>
<td>187</td>
<td>162</td>
<td>+6</td>
</tr>
<tr>
<td>MEAN</td>
<td>146</td>
<td>164</td>
<td>160</td>
<td>155</td>
<td>174</td>
<td>164</td>
<td>+8</td>
</tr>
</tbody>
</table>

ΔT = The difference between the mean of the ankle, knee and hip angles for takeoff 1 and takeoff 2. A positive ΔT value indicates that the leg was more extended in takeoff 2 than in takeoff 1.

Table 5.22b. Ankle, Knee and Hip angles at landings 1 and 2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Landing 1 Ankle (°)</th>
<th>Knee (°)</th>
<th>Hip (°)</th>
<th>Landing 2 Ankle (°)</th>
<th>Knee (°)</th>
<th>Hip (°)</th>
<th>ΔL (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>134</td>
<td>162</td>
<td>163</td>
<td>139</td>
<td>162</td>
<td>173</td>
<td>+5</td>
</tr>
<tr>
<td>DDA</td>
<td>150</td>
<td>169</td>
<td>161</td>
<td>146</td>
<td>172</td>
<td>160</td>
<td>0</td>
</tr>
<tr>
<td>GCG</td>
<td>156</td>
<td>167</td>
<td>163</td>
<td>161</td>
<td>170</td>
<td>174</td>
<td>+7</td>
</tr>
<tr>
<td>AKS</td>
<td>142</td>
<td>158</td>
<td>172</td>
<td>142</td>
<td>159</td>
<td>176</td>
<td>+2</td>
</tr>
<tr>
<td>CJP</td>
<td>146</td>
<td>163</td>
<td>143</td>
<td>141</td>
<td>156</td>
<td>144</td>
<td>-4</td>
</tr>
<tr>
<td>MEAN</td>
<td>146</td>
<td>164</td>
<td>160</td>
<td>146</td>
<td>164</td>
<td>165</td>
<td>+2</td>
</tr>
</tbody>
</table>

ΔL = The difference between the mean of the ankle, knee and hip angles for landing 1 and landing 2. A positive ΔL value indicates that the leg was more extended in landing 2 than in landing 1.

Table 5.22c. Ankle, Knee and Hip angular velocities at takeoffs 1 and 2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Takeoff 1 Ankle (°.s⁻¹)</th>
<th>Knee (°.s⁻¹)</th>
<th>Hip (°.s⁻¹)</th>
<th>Takeoff 2 Ankle (°.s⁻¹)</th>
<th>Knee (°.s⁻¹)</th>
<th>Hip (°.s⁻¹)</th>
<th>ΔT (°.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>326</td>
<td>579</td>
<td>450</td>
<td>457</td>
<td>657</td>
<td>492</td>
<td>84</td>
</tr>
<tr>
<td>DDA</td>
<td>564</td>
<td>358</td>
<td>263</td>
<td>807</td>
<td>603</td>
<td>406</td>
<td>210</td>
</tr>
<tr>
<td>GCG</td>
<td>357</td>
<td>423</td>
<td>356</td>
<td>797</td>
<td>744</td>
<td>538</td>
<td>314</td>
</tr>
<tr>
<td>AKS</td>
<td>437</td>
<td>606</td>
<td>513</td>
<td>536</td>
<td>685</td>
<td>497</td>
<td>54</td>
</tr>
<tr>
<td>CJP</td>
<td>392</td>
<td>759</td>
<td>556</td>
<td>649</td>
<td>984</td>
<td>658</td>
<td>195</td>
</tr>
<tr>
<td>MEAN</td>
<td>415</td>
<td>545</td>
<td>428</td>
<td>649</td>
<td>735</td>
<td>518</td>
<td>171</td>
</tr>
</tbody>
</table>

ΔT = The difference between the mean of the ankle, knee and hip angular velocities for takeoff 1 and takeoff 2. A positive ΔT value indicates that the leg was extending more rapidly in takeoff 2 than in takeoff 1.

Table 5.22d. Ankle, Knee and Hip angular velocities at landings 1 and 2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Landing 1 Ankle (°.s⁻¹)</th>
<th>Knee (°.s⁻¹)</th>
<th>Hip (°.s⁻¹)</th>
<th>Landing 2 Ankle (°.s⁻¹)</th>
<th>Knee (°.s⁻¹)</th>
<th>Hip (°.s⁻¹)</th>
<th>ΔL (°.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>-6</td>
<td>-70</td>
<td>-94</td>
<td>-19</td>
<td>-172</td>
<td>-194</td>
<td>-71</td>
</tr>
<tr>
<td>DDA</td>
<td>18</td>
<td>23</td>
<td>-38</td>
<td>-78</td>
<td>-122</td>
<td>-80</td>
<td>-95</td>
</tr>
<tr>
<td>GCG</td>
<td>2</td>
<td>-38</td>
<td>-123</td>
<td>-92</td>
<td>-127</td>
<td>-193</td>
<td>-84</td>
</tr>
<tr>
<td>AKS</td>
<td>-17</td>
<td>-94</td>
<td>-143</td>
<td>32</td>
<td>-27</td>
<td>-50</td>
<td>70</td>
</tr>
<tr>
<td>CJP</td>
<td>5</td>
<td>-50</td>
<td>-118</td>
<td>16</td>
<td>-40</td>
<td>-141</td>
<td>-1</td>
</tr>
<tr>
<td>MEAN</td>
<td>0</td>
<td>-46</td>
<td>-103</td>
<td>-28</td>
<td>-98</td>
<td>-132</td>
<td>-36</td>
</tr>
</tbody>
</table>

ΔL = The difference between the mean of the ankle, knee and hip angular velocities for landing 1 and landing 2. A positive ΔL value indicates that the leg was extending more rapidly in landing 2 than in landing 1.
Inverse Dynamics - Calculations

The same divisions of the jumps into takeoffs and landings were used for the data from the inverse dynamic analyses to compare the two different actions. Figure 5.8. shows a stick image representation of a single frame for subject AAC during the counter movement jump. The accompanying muscle moment calculation provides a sample of data for this single image. Suffix 'i' ranges from 1 to 4, with segment 1 being the foot, 2 the shank, 3 the thigh and 4 the HAT. With four links there are three joints, ankle (i=1), knee (i=2) and hip (i=3). The ground reaction forces and ground contact moments have been subscripted 0. \( M_0 = \) zero since the force vector as acting though the centre of pressure and therefore has a zero moment arm).

The equation to determine the quasi-static estimate of the muscle moment is also included at the end of the inverse dynamic analysis and uses the notation as shown in Figure 5.8.

Notation for Figure 5.8 and sample calculations on page 169.

- \( m_i \) = mass of segment \( i \)
- \( Y_{(i)} \) and \( Z_{(i)} \) = the planar coordinates of joint centre \( i \)
- \( a_x(i) \) and \( a_y(i) \) = the vertical and horizontal accelerations of the mass centre of segment \( i \)
- \( F_z(i) \) and \( F_y(i) \) = the vertical and horizontal forces acting at the joint centre \( i \)
- \( a_y \) = The point of force application in the \( y \) direction on the force plate surface
- \( I_{(i)} \) = moment of inertia about mass centre of segment \( i \)
- \( \alpha_{(i)} \) = angular acceleration of segment \( i \)
- \( M_{(i)} \) = net moment acting about joint \( i \)
- \( M_s \) = lower limb support moment, (sum of the lower limb joint extension moments)
- \( g \) = gravitational acceleration (-9.81 m.s\(^{-2}\))
- \( d_y_{p(i)}, d_z_{p(i)} \) = the moment arm lengths from the proximal \( (p) \) end of segment \( i \) relative to the segment mass centre in the horizontal \( (y) \) and vertical directions \( (z) \).
- \( d_y_{d(i)}, d_z_{d(i)} \) = the moment arm lengths from the distal \( (d) \) end of segment \( i \) relative to the segment mass centre in the horizontal \( (y) \) and vertical directions \( (z) \)
- \( d_y_{d(0)}, d_z_{d(0)} \) = the moment arm lengths from the centre of pressure on the force plate to the mass centre of the foot segment in the \( (y) \) and \( (z) \) directions.
- \( \dot{y}(a_y) \) = horizontal linear acceleration
- \( \ddot{z} (a_y) \) = vertical linear acceleration
- \( \theta \) = segment orientation angle
- \( \ddot{\theta} (\alpha) \) = segment angular acceleration
- \( \phi \) = relative joint angle
- \( \dot{\phi} (\omega) \) = relative joint angular velocity
Sample calculation for Subject AAC, frame #125, subject mass = 73.10 kg.

Inverse Dynamic Analysis:

Resolving vertically for segment i

\[ \Sigma F_z = m \ddot{z} \]
\[ F_{z(i-1)} + F_{z(i)} + m(i)g = m(i)\ddot{z}(i) \]
\[ F_{z(i)} = m(i)\ddot{z}(i) - F_{z(i-1)} - m(i)g \]

When \( i = 1 \)
\[ F_{z1} = 2.003 \times -0.182 - 1032.00 - 2.003 \times (-9.81) = -1012.72 \text{ N} \]

When \( i = 2 \)
\[ F_{z2} = 6.33 \times 0.053 - 1012.72 - 6.33 \times (-9.81) = -950.57 \text{ N} \]

When \( i = 3 \)
\[ F_{z3} = 20.709 \times 1.987 - 950.57 - 20.709 \times (-9.81) = -706.70 \text{ N} \]

Resolving Horizontally for segment i

\[ \Sigma F_y = m \ddot{y} \]
\[ F_{y(i-1)} + F_{y(i)} = m(i)\ddot{y}(i) \]
\[ F_{y(i)} = m(i)\ddot{y}(i) - F_{y(i-1)} \]

When \( i = 1 \)
\[ F_{y1} = 2.003 \times -0.300 - 6.00 = -6.60 \text{ N} \]

When \( i = 2 \)
\[ F_{y2} = 6.330 \times -3.085 - 6.60 = -26.13 \text{ N} \]

When \( i = 3 \)
\[ F_{y3} = 20.709 \times -2.467 -26.13 = -76.5 \text{ N} \]

Taking Moments about mass centre for segment i

\[ \Sigma M = I \alpha \]
\[ M(i-1) + M(i) + F_{z(i-1)}dYd(i) + F_{y(i-1)}dzd(i) + F_{z(i)}dyp(i) + F_{y(i)}dzp(i) = I(i)\alpha(i) \]
\[ M(i) = I(i)\alpha(i) - M(i-1) - F_{z(i-1)}dyd(i) - F_{y(i-1)}dzd(i) - F_{z(i)}dyp(i) - F_{y(i)}dzp(i) \]

When \( i = 1 \) (Joint = Ankle)
\[ M(1) = 0.006 \times 0.818 - 0.000 - 1032 \times 0.079 - 6.000 \times 0.036 - 1012.72 \times 0.051 - 6.60 \times 0.051 \]
\[ M_a = -133.724 \text{ N.m} \]

When \( i = 2 \) (Joint = Knee)
\[ M(2) = 0.0809 \times 16.496 - 133.736 + 1012.72 \times 0.150 - 6.60 \times 0.194 + 950.57 \times 0.102 - 26.13 \times 0.133 \]
\[ M_k = 111.709 \text{ N} \]

When \( i = 3 \) (Joint = Hip)
\[ M(3) = 0.201 \times -14.632 + 111.709 - 950.57 \times 0.139 - 26.13 \times 0.146 - 706.70 \times 0.117 - 77.22 \times 0.121 \]
\[ M_h = -119.204 \text{ N.m} \]
\[ M_s = M_k - M_a - M_h = 111.709 - (-133.724) - (-119.204) = 365 \text{ N.m} \]

Quasi-Static Analysis:

\[ M(i) = (F_{z(i-1)} \times (Y(i) - a_j)) - (F_{y(i-1)} \times Z(i)) \]

When \( i = 1 \)
\[ M_1 = (1032 \times (-0.132 - 0.002)) - (6.0 \times 0.056) = -138.624 \text{ N.m} \]

When \( i = 2 \)
\[ M_2 = (1032 \times (0.112 - 0.002)) - (6.0 \times 0.390) = 111.180 \text{ N.m} \]

When \( i = 3 \)
\[ M_3 = (1032 \times (-0.125 - 0.002)) - (6.0 \times 0.670) = -135.084 \text{ N.m} \]
\[ M_s = M_k - M_a - M_h = 111.180 - (-138.624) - (-135.084) = 385 \text{ N.m} \]
Figure 5.8. Four link model of foot, shank, thigh and HAT segments, plus the Free Body Diagram for the shank segment for subject AAC.
In addition, muscle moment power \( (P_{mm}) \) and energy \( (E_{mm}) \) were determined. Muscle moment power was obtained by multiplying the calculated muscle moment at joint \( i \) \( (MM_i) \) by the relative angular velocity of the segments forming joint \( i \) \( (\omega_i) \).

\[
P_{mm} = MM_i \times \omega_i
\]

Muscle moment energy \( (E_{mm}) \) was determined by integrating the muscle moment power time curve with respect to time.

\[
E_{mm} = \int (P_{mm} \times \omega_i) \delta t
\]

The process of integration was used to calculate the area under the power-time curve, with positive values indicating concentric muscular work and negative values eccentric muscular work. The power-time curves for subject AAC during tof1 have been shown in Figure 5.9. To enable comparisons between subjects of different sizes, all time, moment, power and energy data were normalised. Time was represented on a percentage scale from 0% to 100%. Muscle moment data values were divided by body mass, gravitational acceleration and leg length. The height of the hip marker at time zero in the CMJ was used to define leg length. In this way the N.m values determined by the inverse dynamic analyses were converted into dimensionless units. To convert the muscle moment power data into normalised units each value was divided by body mass to produce values in W.kg\(^{-1}\) (Figure 5.10). Energy data were also effectively normalised by integrating the normalised power-time data to produce units of J.kg\(^{-1}\). Figure 5.11 illustrates the relationship between joint muscle moment and joint angular velocity. When both have the same sign, the work is concentric and when the signs are opposite the work is eccentric. In Figure 5.8 and in the sample calculation on page 170, positive has been shown to be in the anti-clockwise direction. In the analyses, the forces producing leg extension have been regarded as positive. That is all angular velocities, moments and hence power values have been based on a common 'positive=extension' convention. In addition the lower limb support moments as defined by Winter (1980) have been calculated. Since the moments producing leg extension have been defined as positive, the support moment \( (M_s) \) is defined as the sum of the three joint moments.

\[
M_s = M_a + M_k + M_h
\]

where \( M_s \) = Support Moment, \( M_a \) = Ankle moment, \( M_k \) = Knee moment and \( M_h \) = hip moment

Takeoffs one and two have been compared to enable secondary question (i) to be answered. With data for five trials direct comparisons between individual trials rather than statistical analyses have been made.
Figure 5.9. Ankle, Knee and Hip Muscle Moment Power (W) against takeoff time (s) for subject AAC during takeoff 1.

Figure 5.10. Normalised Ankle, Knee and Hip Muscle Moment Power (W. kg$^{-1}$) against takeoff time as a percentage for subject AAC during takeoff 1.

Figure 5.11. Relationship between muscle moment (M) and joint angular velocity ($\omega$) when determining concentric (C) and eccentric (E) work.
The moment time histories for each phase of each jump were obtained and angular impulse was calculated for the positive moment phase of each takeoff and landing. That is the area under the positive moment time curve was obtained, by numerical integration, to produce a single impulse value for each joint for the two takeoffs and two landings per subject. These were summed, and each joint's contribution expressed as a percentage contribution to the total angular impulse.

The process of inverse dynamics relies upon inertia data and kinematics at the input stage, and therefore was likely to be influenced by the choice of body segment inertia parameters and the level of data filtering incorporated into the analyses. The takeoff and landing actions were re-analysed using the Winter inertia data and the raw coordinate data to enable comparisons between the moments, power, energy and angular impulse data to evaluate the influence of these two factors on the results. (Graphs of these comparisons are in Appendices A5.7 and A5.8).

**Resultant Muscle Moments**

The phasing of the muscle moments produced by each subject was different. By using the normalised takeoff and landing actions, direct comparisons between the patterns of the muscle moment curves produced by the subjects could be made. Figure 5.12 summarises the two takeoff actions for the five subjects. In each graph the line style coding remains constant. The two sets of graphs have been plotted on the same scale. The support moments ranged from peaks of 0.99 to 1.29 for tof1 and from 0.40 to 1.15 for tof2. Four subjects followed a similar pattern with the support moment being the largest value. Subject CJP also followed this pattern for tof1, but tof2 was different. The largest muscle moment was present at the knees, with the ankles and hips making negative contributions at this time. By definition the support moment is the sum of the extension moments at the ankles, knees and hips, and so the only way in which the knee moment can exceed the support moment would be for the ankles and knees to be flexing. This was not the case. Therefore the data for tof2 were suspect. A number of possibilities have been examined, and an additional section of the results introduced to investigate the factors which could have contributed to this unusual observation.

Figure 5.12 illustrates the normalised muscle moment data for the two takeoff actions for the five analysed subjects. In each graph the ankle, knee and hip moment curves have been plotted. In four out of the five cases, the peak support moment was greater in tof1 than in tof2. Subject AAC was the exception, however, as shown in Table 5.20d, this subject was the only one to produce greater forces as the bottom of the squat in the RBJ phase than in the CMJ phase. The timing of the moment peaks varied considerably. For tof1, four out of the five subjects followed a pattern with the hip moments peaking first (3%), followed by the knees (11%) and ending with the ankles (57%). Subject AAC was different with the knees peaking first at 12%, followed by the ankles at 15% and the hips at 54%. For tof2 the pattern of peaking was similar, although the
Figure 5.12. Ankle, Knee, Hip and Support Muscle Moments for takeoffs 1 and 2, normalised by body weight and leg length.
Figure 5.13. Ankle, Knee, Hip and Support Muscle Moments for landings 1 and 2, normalised by body weight and leg length.
first two peaks occurred later with the hips at 13% and the knees at 24%. The hips peaked at about 56% of the action. Subject CJP's data for tof₂ were ignored at this stage of the analysis.

The graphs in Figure 5.13 showed that the peak support moments were larger in ldg₂ than in ldg₁. Once again the pattern for subject CJP was different to those of the other subjects. The support moments were either less than or the same as the peak moments for the knee joint. The peak values for the moments during landings ranged from 0.70 to 1.16 for ldg₁ and from 0.90 to 1.23 for ldg₂. The order for the peaking of the joint moments was less clear in the landing actions than for the takeoffs. There were double peaks in all the trials and the range of sequences varied from subject GCG who appeared to achieve peaks at approximately 33% of the action in all joints for ldg₁ and at 55% of the action in all joints for ldg₂. Subject AKS followed the same order of peaking from hip to ankle to knee for both landings, but the remaining three subjects showed no particular pattern between the two landing actions. The final values of the moments were lower for ldg₂ than for ldg₁, but as the peak vertical force at the bottom of the squat was greater for ldg₁ than for ldg₂ this was expected.

Joint Relative Angular Velocity

Joint angular velocities have been summarised in Tables 5.20e and Table 5.22c. It was evident that there were differences between joint angular velocities at takeoff and landing. To study the pattern of development of the joint angular velocities at each of the joints Figures 5.14 and 5.15 were produced. In a similar manner to the muscle moment graphs in Figures 5.12 and 5.13, a common notation has been used and the plots with toff₁ and tof₂ having been arranged alongside each other for comparative purposes. A summed angular velocity was also calculated. This was the sum of the three angular velocities and provided a maximum value for a "pseudo joint" angular velocity. The most striking aspect of the data was that the joint angular velocities for tof₂ appear to be peaking or even increasing at the instant of takeoff. This is in contrast to the toff₁ plots where the peaks occurred between 80% and 90% through the takeoff action. All the takeoff values were greater in tof₂ than in toff₁. During the landing actions, the minimum angular velocities occurred earlier in ldg₁ (less than 30% into landing) than in ldg₂ (between 20% and 45% into landing) and in all cases were smaller in value indicating more rapid flexions in all joints.
Figure 5.14. Relative angular velocity (rad.s⁻¹) of Ankle, Knee and Hip for takeoffs 1 and 2, plus the Summed values for leg extension.
Figure 5.15. Relative angular velocity (rad.s⁻¹) of Ankle, Knee and Hip for landings 1 and 2, plus the Summed values for leg flexion.
Muscle Moment Power and Energy

The joint angular velocities were multiplied by the muscle moments for each joint to obtain the muscle moment power graphs which have been presented in Figures 5.16 and 5.17. The same scales and a common notation have been used with the support muscle moment power graphs being defined as the sum of the three joint muscle moment powers. The order of peaking for the muscle moment power ($P_{mm}$) values for four of the subjects at $tof_1$ was hip, knee and then ankle. The ankle and knee peaks occurred at almost the same time for subject AAC. The order for subject CJP was different with knee peaking at 58%, followed by the ankle at 82% and the hip at 93%. The support $P_{mm}$ values, listed in Table 5.23a, peaked between 62% and 80% of the action and the normalised values ranged from 36 W.kg$^{-1}$ to 70 W.kg$^{-1}$. In Table 5.23b, the equivalent $P_{mm}$ values for landings 1 and 2 have been summarised. Three of the five subjects in $ldg_1$, displayed a peaking order of knee, ankle, hip whilst the other two subjects peaked in the order hip, ankle, knee and ankle, hip, knee. The normalised peak support $P_{mm}$ values ranged from -38 W.kg$^{-1}$ to -78 W.kg$^{-1}$ for $ldg_1$, and from -31 W.kg$^{-1}$ to -58 W.kg$^{-1}$ for $ldg_2$. The peaks of support $P_{mm}$ occurred from 27% to 42% of $ldg_1$ and from 24% to 55% of $ldg_2$.

Table 5.23a. Lower Limb Muscle Moment Power data for takeoffs 1 and 2. Percentage of action at which the Peak Value occurred and Peak value at that time (W.kg$^{-1}$).

<table>
<thead>
<tr>
<th>Support</th>
<th>$tof_1$</th>
<th>$tof_2$</th>
<th>$tof_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{mm}$</td>
<td>%</td>
<td>W.kg$^{-1}$</td>
<td>%</td>
</tr>
<tr>
<td>AAC</td>
<td>74</td>
<td>58.6</td>
<td>78</td>
</tr>
<tr>
<td>DDA</td>
<td>64</td>
<td>46.0</td>
<td>73</td>
</tr>
<tr>
<td>GCG</td>
<td>62</td>
<td>36.3</td>
<td>71</td>
</tr>
<tr>
<td>AKS</td>
<td>80</td>
<td>31.0</td>
<td>82</td>
</tr>
<tr>
<td>CJP</td>
<td>78</td>
<td>69.7</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 5.23b. Lower Limb Muscle Moment Power data for landings 1 and 2. Percentage of action at which the Peak Value occurred and Peak value at that time.

<table>
<thead>
<tr>
<th>Support</th>
<th>$ldg_1$</th>
<th>$ldg_1$</th>
<th>$ldg_2$</th>
<th>$ldg_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{mm}$</td>
<td>%</td>
<td>W.kg$^{-1}$</td>
<td>%</td>
<td>W.kg$^{-1}$</td>
</tr>
<tr>
<td>AAC</td>
<td>42</td>
<td>-46.4</td>
<td>52</td>
<td>-58.0</td>
</tr>
<tr>
<td>DDA</td>
<td>31</td>
<td>-42.9</td>
<td>43</td>
<td>-39.2</td>
</tr>
<tr>
<td>GCG</td>
<td>38</td>
<td>-78.4</td>
<td>55</td>
<td>-43.0</td>
</tr>
<tr>
<td>AKS</td>
<td>27</td>
<td>-38.3</td>
<td>24</td>
<td>-32.8</td>
</tr>
<tr>
<td>CJP</td>
<td>30</td>
<td>-52.7</td>
<td>36</td>
<td>-30.9</td>
</tr>
</tbody>
</table>
There were obvious variations in the strategies used by the subjects. To determine the work contributed by each joint to each action, the area under the $P_{mm}$ curve was summed. Each joint's contribution was then expressed as a percentage of the total work. Normalised data have been presented in Figures 5.18 and 5.19 to illustrate the variations in energy throughout each action. In addition, the work done in Joules and the normalised work in $(\text{J} \cdot \text{kg}^{-1})$ have been calculated for each of the phases of the actions and presented in Tables 5.24a and 5.24b respectively.

Table 5.24a. Lower Limb Muscle Moment Energy for takeoffs and landings 1 and 2. (J)

<table>
<thead>
<tr>
<th></th>
<th>$t_{of1}$</th>
<th>$t_{of2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ankle</td>
<td>knee</td>
</tr>
<tr>
<td>AAC</td>
<td>165.2</td>
<td>183.6</td>
</tr>
<tr>
<td>DDA</td>
<td>153.9</td>
<td>56.5</td>
</tr>
<tr>
<td>GCG</td>
<td>95.2</td>
<td>101.3</td>
</tr>
<tr>
<td>AKS</td>
<td>45.2</td>
<td>135.7</td>
</tr>
<tr>
<td>Mean</td>
<td>114.9</td>
<td>119.3</td>
</tr>
</tbody>
</table>

Table 5.24b. Normalised Lower Limb Muscle Moment Energy for takeoffs and landings 1 and 2. (J. kg$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>$t_{of1}$</th>
<th>$t_{of2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ankle</td>
<td>knee</td>
</tr>
<tr>
<td>AAC</td>
<td>-84.0</td>
<td>-200.8</td>
</tr>
<tr>
<td>DDA</td>
<td>-129.6</td>
<td>-63.4</td>
</tr>
<tr>
<td>GCG</td>
<td>-124.9</td>
<td>-191.8</td>
</tr>
<tr>
<td>AKS</td>
<td>-57.6</td>
<td>-214.4</td>
</tr>
<tr>
<td>Mean</td>
<td>-99.0</td>
<td>-167.6</td>
</tr>
</tbody>
</table>

All energy values have been calculated from the bottom of the squat until loss of ground contact for takeoffs and from impact to the bottom of the squat for landings. Positive values = concentric work and negative values = eccentric work. All data in Table 5.24b have been normalised by dividing the work in Joules by the subject's body mass in kg.
Two subjects produced more muscle moment work in \( t_{of2} \) than in \( t_{of1} \) (GCG and AKS). Subject AAC contributed considerably more work in \( t_{of1} \) than in \( t_{of2} \) and subject DDA completed equivalent work in both takeoffs. For the landings, subject AKS contributed equivalent negative work in both landings but subjects AAC, DDA and GCG produced more eccentric work in \( l_{dg1} \) than \( l_{dg2} \). To investigate the strategies employed by each subject, the contributions made by each joint, expressed as percentages, have been summarised in Table 5.25.

Table 5.25. Normalised Lower Limb Muscle Moment Energy for takeoffs and landings 1 and 2. (% of total leg extension work).

<table>
<thead>
<tr>
<th></th>
<th>( t_{of1} )</th>
<th></th>
<th>( t_{of2} )</th>
<th></th>
<th>( t_{of1} )</th>
<th></th>
<th>( t_{of2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>36</td>
<td>40</td>
<td>24</td>
<td>23</td>
<td>54</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>DDA</td>
<td>49</td>
<td>18</td>
<td>32</td>
<td>42</td>
<td>14</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>GCG</td>
<td>31</td>
<td>33</td>
<td>36</td>
<td>26</td>
<td>31</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>AKS</td>
<td>19</td>
<td>57</td>
<td>25</td>
<td>20</td>
<td>55</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>39</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td>33</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>( l_{dg1} )</th>
<th></th>
<th>( l_{dg2} )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
<td>Ankle(%)</td>
</tr>
<tr>
<td>AAC</td>
<td>23</td>
<td>55</td>
<td>22</td>
<td>63</td>
</tr>
<tr>
<td>DDA</td>
<td>45</td>
<td>22</td>
<td>33</td>
<td>72</td>
</tr>
<tr>
<td>GCG</td>
<td>28</td>
<td>43</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>AKS</td>
<td>18</td>
<td>67</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Mean</td>
<td>32</td>
<td>40</td>
<td>28</td>
<td>47</td>
</tr>
</tbody>
</table>

The values in Table 5.25 have been calculated from the data in Table 5.24 with the contributions from the three joints being summed to determine the total work. Each joint contribution has been expressed as a percentage of the total work. A negative percentage, indicates that the work at the joint was opposing the joint motion. Data in Tables 5.23 to 5.25 were based on Zatsiorsky filtered data for filmed trial.

Subject GCG shared the work evenly between the three joints in \( t_{of1} \). In \( t_{of2} \) however, the hips contributed 43% of the work compared to 26% from the ankles and 31% from the knees. For subject AAC and particularly for subject AKS, the work contributed by the knees in \( t_{of1} \) was dominant at 40% and 57% respectively. In \( t_{of2} \), the corresponding figures increased to 54% and 55%. Subject DDA contributed half the work from the ankles in \( t_{of1} \) and 32% from the hips. In \( t_{of2} \) these figures changed to be just over 40% from these two joints. In both takeoffs the knees produced less than 20% of the work for subject DDA. In summary, all four subjects retained the general pattern of work at the joints for \( t_{of2} \) that they used in \( t_{of1} \). One subject increased the contribution by the knees, two increased the contribution from the hips, and one reproduced virtually the same pattern in both takeoffs. In the landings three subjects used a knee dominated strategy in \( l_{dg1} \), and two subjects used an ankle dominated strategy in \( l_{dg2} \). Of the two subjects who retained a knee dominated strategy in both landings, one increased the contribution from the knees in \( l_{dg2} \) compared to \( l_{dg1} \), whereas the other retained the same pattern by sharing the work between the three joints. One subject (AAC) changed from a knee dominated approach in \( l_{dg1} \) to an ankle and hip dominated strategy in \( l_{dg2} \). Two subjects (AAC, DDA) did more total
muscle moment work in tof₁ than tof₂. The other two subjects (GCG, AKS) reversed this trend with at least 30% more work being contributed in tof₂ than in tof₁. In the landings the differences between the total work being done were not as marked, with two subjects (AAC, AKS) contributing similar amounts of work to both landings and two doing more work in ldg₁ than in ldg₂ (DDA, GCG). The similarities were not displayed by the same pairs of subjects in takeoffs and landings. Table 5.24b summarises the work by each subject normalised to body weight together with the means for each phase also being included. The mean normalised work in tof₁ was the same as that in tof₂, but the work in ldg₁ was about 15% greater than that for ldg₂.
Figure 5.16. Support, Ankle, Knee and Hip Muscle Moment Power for takeoffs 1 and 2, normalised by body mass (W.kg⁻¹).
Figure 5.17. Support, Ankle, Knee and Hip Muscle Moment Power for landings 1 and 2, normalised by body mass (W.kg⁻¹).
Figure 5.18. Normalised Support, Ankle, Knee and Hip Muscle Moment Energy for takeoffs 1 and 2.
Figure 5.19. Normalised Support, Ankle, Knee and Hip Muscle Moment Energy for landings 1 and 2.
Angular Impulse

The angular impulse ($\langle MM.\delta t \rangle$) values for the takeoffs and landings have been summarised in Tables 5.26a and 5.26b. The Mean values have been determined using the data for the first four subjects, and do not include the anomalous data for subject CJP. The mean values provide a single score for each joint's contribution for each phase of the action.

The total support angular impulse values were either the same or greater for tof$_1$ than for tof$_2$. The profile of angular impulses for the landings, summarised in Table 5.26b, reflect a very similar pattern of distribution for the three joints. The mean values of 35%, 44% and 20% for ldg$_1$ and ldg$_2$ were identical. However, the individual trials did not reflect this. For example, subject AAC used the ankle and knee extensors equally for ldg$_1$ but for ldg$_2$ the ankle was dominant with over 50% of the total angular impulse being contributed by this joint. Subject DDA followed a similar pattern to subject AAC, but subjects GCG and AKS maintained an equal and dominant contribution from the ankles and knees with a lower than 20% contribution from the hip extensors in both landing actions.

Table 5.26a. Angular impulse contributions as percentages of the lower limb support moment impulses for takeoffs one and two.

<table>
<thead>
<tr>
<th></th>
<th>tof$_1$</th>
<th></th>
<th>tof$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
</tr>
<tr>
<td>AAC</td>
<td>37</td>
<td>41</td>
<td>22</td>
</tr>
<tr>
<td>DDA</td>
<td>32</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>GCG</td>
<td>27</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>AKS</td>
<td>31</td>
<td>42</td>
<td>27</td>
</tr>
<tr>
<td>MEAN</td>
<td>32</td>
<td>39</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5.26b. Angular impulse contributions as percentages of the lower limb support moment impulses for landings one and two.

<table>
<thead>
<tr>
<th></th>
<th>ldg$_1$</th>
<th></th>
<th>ldg$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
</tr>
<tr>
<td>AAC</td>
<td>43</td>
<td>41</td>
<td>15</td>
</tr>
<tr>
<td>DDA</td>
<td>44</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>GCG</td>
<td>44</td>
<td>38</td>
<td>17</td>
</tr>
<tr>
<td>AKS</td>
<td>39</td>
<td>47</td>
<td>13</td>
</tr>
<tr>
<td>MEAN</td>
<td>44</td>
<td>38</td>
<td>19</td>
</tr>
</tbody>
</table>

Data in Tables 5.26a and 5.26b were based on Zatsiorsky filtered data for filmed trial.

The four subjects produced approximately one third of the angular impulse from each joint during tof$_1$. In contrast, during ldg$_2$, these four subjects shared the impulse between the three joints in a distal to proximal manner, with the ankle being dominant (44%), followed by the knee (33%) and ending with the hip (23%).
Influence of Inertia Data and Filtering

The influences of kinematic data filtering and of the use of two different inertia data sets were investigated by comparing the calculated muscle moment energy and angular impulse data in selected phases of the Marey jumping. In Table 5.27, the percentage data for the four possible combinations of calculated energy have been summarised for tof\textsubscript{1}.

Table 5.27. Mean Muscle Moment Energy contributions for takeoff 1, using Raw(R) and Filtered (F) kinematic data and Winter (W) and Zatsiorsky (Z) inertia data.

<table>
<thead>
<tr>
<th>tof\textsubscript{1}</th>
<th>Ankle</th>
<th>FZ(%)</th>
<th>RZ(%)</th>
<th>FW(%)</th>
<th>RW(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>36</td>
<td>37</td>
<td>33</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>DDA</td>
<td>49</td>
<td>50</td>
<td>49</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>GCG</td>
<td>31</td>
<td>30</td>
<td>31</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>AKS</td>
<td>18</td>
<td>16</td>
<td>21</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>FZ(%)</td>
<td>RZ(%)</td>
<td>FW(%)</td>
<td>RW(%)</td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>40</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>DDA</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>GCG</td>
<td>33</td>
<td>35</td>
<td>32</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>AKS</td>
<td>57</td>
<td>56</td>
<td>63</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>FZ(%)</td>
<td>RZ(%)</td>
<td>FW(%)</td>
<td>RW(%)</td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>24</td>
<td>21</td>
<td>25</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>DDA</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>GCG</td>
<td>36</td>
<td>35</td>
<td>37</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>AKS</td>
<td>25</td>
<td>28</td>
<td>16</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

The muscle moment energy percentage contributions to tof\textsubscript{1} were very similar for all subjects irrespective of the inertia data set used and whether or not the Butterworth filtering process had been employed. However, the combination of filtering and inertia data did influence the total energy measured in Joules for each subject. For example, subject AAC generated 466 Joules using the unfiltered 'Z' data compared with 460 Joules when the unfiltered 'W' data were employed. The most varied set of data was found for subject GCG. In this case the data ranged from 213 J, for the unfiltered 'W' data, to 307 for the filtered 'Z' data. However, these variations in magnitude did not influence the relative contributions made by the separate joints.

The possible influences of the different inertia data sets and kinematic data processing were also investigated for angular impulses. The variations between subjects was less marked than for the joint energy contributions and so only mean data for each joint have been reported. Table 5.28 includes data for tof\textsubscript{1} and ldg\textsubscript{2}. Since time rather than velocity data were used in combination with the resultant joint moments, it is not surprising that the angular impulse data were less variable than the equivalent energy values.
Table 5.28. Mean Angular impulse contributions for takeoff 1 and landing 2, using Raw(R) and Filtered (F) kinematic data and Winter (W) and Zatsiorsky (Z) inertia data.

<table>
<thead>
<tr>
<th></th>
<th>Takeoff 1</th>
<th></th>
<th>Landing 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankle(%)</td>
<td>Knee(%)</td>
<td>Hip(%)</td>
</tr>
<tr>
<td>WR</td>
<td>31</td>
<td>38</td>
<td>31</td>
</tr>
<tr>
<td>ZR</td>
<td>32</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>WF</td>
<td>31</td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>ZF</td>
<td>32</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>WR</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>ZR</td>
<td>42</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>WF</td>
<td>43</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td>ZF</td>
<td>44</td>
<td>33</td>
<td>23</td>
</tr>
</tbody>
</table>

W = Winter inertia data, Z = Zatsiorsky inertia data, R = raw coordinate data, F = filtered coordinate data.

The primary purpose within the inverse dynamics analysis section was to determine whether differences existed between the two takeoff and landing actions, rather than to quantify the energy or impulse values specifically. Therefore as it appeared that the choice of inertia data and, to a certain extent the use of the Butterworth filtering process, was not a major concern. The need to expand the analyses to cover all four combinations of data was removed and so the final analysis, that is the use of a simplified quasi-static approximation to the muscle moments was considered.

Quasi-static analysis

Although limited in its application to activities in which ground reaction forces can be measured, the quasi-static technique for determining muscle moments has the great advantages of simplicity of measurement and independence from segmental inertia parameters. The question to be answered was

could this quasi-static technique provide reliable muscle moment, and segmental energy data which would compare acceptably with the data obtained by inverse dynamics?

To answer this question, the same force and joint centre coordinate data used in the inverse dynamics analyses were used and the equation reported on page 169 was employed. This is a modification to the method described by Alexander and Vernon (1975), which is more convenient for use with computerised data files. Root mean squared differences (RMSD) between the moments determined by inverse dynamics (id) and quasi-statics (qs) were calculated and expressed as percentages of the ranges of the id values for the separate joint moments and for the overall lower limb support moments.
To examine the possible influence of impacts on the calculations, one of the takeoffs and one of the landings for each subject (except CJP) were included in the comparisons. The id data sets used as the criterion were those based on the Zatziorsky inertia data with the Butterworth filtered kinematics.

Table 5.29. Differences between Resultant Muscle Moments calculated using Inverse Dynamic (id) and Quasi-Static (qs) analysis techniques.

<table>
<thead>
<tr>
<th></th>
<th>Ankle (%)</th>
<th>Knee (%)</th>
<th>Hip (%)</th>
<th>Support (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>0.6</td>
<td>4.5</td>
<td>16.0</td>
<td>7.2</td>
</tr>
<tr>
<td>DDA</td>
<td>0.6</td>
<td>3.8</td>
<td>11.4</td>
<td>6.2</td>
</tr>
<tr>
<td>GCG</td>
<td>0.5</td>
<td>3.0</td>
<td>10.2</td>
<td>5.9</td>
</tr>
<tr>
<td>AKS</td>
<td>1.4</td>
<td>9.6</td>
<td>25.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Mean</td>
<td>0.8</td>
<td>5.2</td>
<td>15.8</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RBJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>0.7</td>
<td>5.8</td>
<td>9.7</td>
<td>8.7</td>
</tr>
<tr>
<td>DDA</td>
<td>0.8</td>
<td>3.5</td>
<td>7.7</td>
<td>10.2</td>
</tr>
<tr>
<td>GCG</td>
<td>0.6</td>
<td>5.1</td>
<td>9.8</td>
<td>9.3</td>
</tr>
<tr>
<td>AKS</td>
<td>0.6</td>
<td>5.0</td>
<td>14.6</td>
<td>12.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.7</td>
<td>4.9</td>
<td>10.5</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AAC</td>
<td>0.3</td>
<td>1.4</td>
<td>2.3</td>
<td>4.4</td>
</tr>
<tr>
<td>DDA</td>
<td>0.7</td>
<td>1.9</td>
<td>3.5</td>
<td>4.3</td>
</tr>
<tr>
<td>GCG</td>
<td>0.5</td>
<td>3.7</td>
<td>8.0</td>
<td>7.1</td>
</tr>
<tr>
<td>AKS</td>
<td>0.6</td>
<td>4.4</td>
<td>14.0</td>
<td>9.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.5</td>
<td>2.9</td>
<td>7.0</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The inverse dynamic analyses based on the 'Z' inertia data and filtered kinematics were used as the criterion against which the quasi-static results were compared. In each case the RMSD has been expressed as a percentage of the range of the criterion data.

Table 5.29 contains a summary of the percentage differences between the quasi-static and inverse dynamics resultant muscle moments. The data followed the same pattern for all subjects with the differences at the ankles being 1% or less. At the knees the differences increased to between 3% and 6%, with means of 5% or less. The variation at the hips was more marked with values ranging up to 16% with the exception of subject AKS with a value of 25%. Surprisingly the poorest agreement overall resulted during the analyses of the CMJ phase of the Marey Jump. The quasi-static technique neglects segment weights and segmental inertia forces and so it might be anticipated that activities in which large accelerations occur, would produce the greatest discrepancies between the two analyses. The results as summarised in Table 5.29 agree with the observations of Alexander and Vernon (1975) for the moments about the ankles and knees, however, no data were presented for the hips.

To investigate whether quasi-statically determined muscle moments could be used to reliably determine the joint energy contributions, the same relative joint angular velocities used in the
inverse dynamic analyses were combined with the new muscle moment data. Any differences in energy would therefore be due to the differences in the muscle moment data only. Inevitably the differences in muscle moments, reported in Table 5.29, would mean that the values of the energy contributions would be different from those obtained using inverse dynamics. However, were these differences any greater than those obtained using inverse dynamics with a different inertia data set, or so different that the relative joint contributions could not be obtained.

would the energy values based on quasi-statically determined resultant muscle moments be useful in quantifying the relative contributions by each of the joints?

Table 5.30. Comparison of Lower Limb Muscle Moment Energy for takeoff 1, (J) using Inverse Dynamics (id) and Quasi-Statics (qs) analysis techniques.

<table>
<thead>
<tr>
<th></th>
<th>(id) ankle</th>
<th>knee</th>
<th>hip</th>
<th>sum</th>
<th>(qs) ankle</th>
<th>knee</th>
<th>hip</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>165.0</td>
<td>184.0</td>
<td>110.0</td>
<td>459.0</td>
<td>168.0</td>
<td>212.0</td>
<td>132.0</td>
<td>512.0</td>
</tr>
<tr>
<td>DDA</td>
<td>154.0</td>
<td>57.0</td>
<td>101.0</td>
<td>311.0</td>
<td>158.0</td>
<td>70.0</td>
<td>125.0</td>
<td>353.0</td>
</tr>
<tr>
<td>GCG</td>
<td>95.2</td>
<td>101.0</td>
<td>111.0</td>
<td>307.0</td>
<td>97.0</td>
<td>113.0</td>
<td>144.0</td>
<td>354.0</td>
</tr>
<tr>
<td>AKS</td>
<td>45.2</td>
<td>136.0</td>
<td>60.0</td>
<td>240.0</td>
<td>45.0</td>
<td>149.0</td>
<td>106.0</td>
<td>300.0</td>
</tr>
<tr>
<td>Mean</td>
<td>114.9</td>
<td>119.0</td>
<td>95.0</td>
<td>329.0</td>
<td>117.0</td>
<td>136.0</td>
<td>127.0</td>
<td>380.0</td>
</tr>
</tbody>
</table>

The data in Table 5.30 shows that the energy calculated for each joint was greater for the quasi-statically technique compared with the criterion inverse dynamic technique. The mean differences were greater by 2% at the ankle, 14% at the knee, 33% at the hip and 15% for the sum of the three lower limb joint contributions. Individual subjects data varied with subject GCG's data being the most unusual showing a zero difference at the ankles, and 10% and 77% differences at the knees and hips respectively. The ordering in terms of contributions made by the joints remained constant throughout both analyses. That is the pattern across all subjects was consistent and appeared to be independent of the analysis method selected. However, the overall contributions made by the joints did vary and was dependant upon the analysis method selected. For example, the mean contribution for the knees remained at 36% irrespective of the analysis selected, but the contribution made by the ankles and hips reversed when using the inverse dynamics technique compared to the quasi-static technique.

In summary, the quasi-static technique overestimated the total work being contributed by each joint in the push off phase of tof₁. The overestimate was largest at the hips and resulted in a misrepresentation of the contribution made by the hip extensors. However, there was evidence to indicate that the quasi-static technique was suitable for establishing the relative contributions made by each joint in tof₁.
Analysis of the data for subject CJP

The data for subject CJP were so different to the other four subjects that it was treated independently. The moment data in Figures 5.12 and 5.13 were clearly in error since the support moments were lower than the contributions from the knees. A number of factors were checked to determine the causes of these anomalies, ranging from:

the correct film and force data files had been combined,
the synchronisation of the force and cinefilm data,
the influence of errors in the point of force application,
the scaling, offset an rotation of the film image coordinates,
the interpolation and differentiation of the image data.

These investigations proved fruitless with the exception of the point of force application. There was the possibility of influencing the resultant muscle moments enough to bring them into line with the theoretically anticipated values if the centre of pressure data were artificially shifted along the force plate to a point that they lay outside the range of the subject's feet. This could only have been possible if the film data had been incorrectly scaled and offset in the earlier calculations. On checking the film images and the position of subject CJP's feet on the force plate it became clear that it was not the explanation. Finally the individual force data records were re-examined to see if the filmed trial was in any way unusual. The force plate data for subject CJP have been presented in Figure 5.20. In each case the mean data and the mean ±1 Standard Deviation have been plotted against time for the vertical force (Fz), the horizontal force (Fy) and the point of force application (ay). The corresponding data for all the subjects has been reproduced in a condensed format in Appendix A5.11. It can be seen that there was no evidence of any unusual data within the six trials for subject CJP.

It has not been possible to explain why the data for subject CJP was so different to the data for the other subjects and why the support moments arising from the analyses showed that the data for parts of the Marey Jump action could not be used. It was therefore not appropriate to use the muscle moment data for subject CJP, or any of the following results, in the overall study. Also, as no explanation for the errors could be found, the results arising from any of the analyses in which the film and force plate data were combined for subject CJP were not used.
Figure 5.20. Force plate data for a the counter movement jumps for subject CJP showing the mean of 6 jumps ±1SD. Takeoff is at time zero.
5:4 DISCUSSION

A substantial part of the analyses at the beginning of the results section focussed on improving the quality of the data to be used in the following inverse dynamic analyses. The results from the preceding chapters had highlighted problems and appropriate methods and procedures which were subsequently adopted. Initially a series of calculations were undertaken to check that the force, film and inertia data were suitable for inverse dynamics analysis purposes.

Limb length data used as a criterion against which the digitised data were compared provided evidence to support the use of the transformation routines adopted in this study. The reported data showed that although the mean limb length errors over each sequence were small at about 2 mm, there was a range of up to 40 mm. The mean errors were less than one percent of the magnitude of the criterion lengths measured directly from the subject. These errors could have arisen from a number of sources including skin/marker movement, digitising errors, lens distortion and film granularity factors, but were comparable with the errors reported by other authors. For example Cappozzo et al. (1993) reported skin marker movement artifacts for 3D analysis of between 10 mm and 20 mm, which convert to approximate length errors in 2D of between 3% and 4% in the current analysis. It would appear therefore that most of the errors obtained could have arisen from marker movement and that an overall error of 5% in the worst case was not unusual. The mean measurement performance for the film analyses used in this study were comparable in accuracy with previously published results (Kennedy et al. 1989; Angulo and Dapena, 1992) and provided confidence in the film processing transformations used.

The inertia data were based on two sources, Winter (1979) and Zatsiorsky and Seluanov (1983). They provided some variation in segmental inertia parameters as listed in Tables 5.7 and 5.8, which had a small impact on the resulting inverse dynamics analyses. Variations in segmental inertia parameters were relatively small and later analyses revealed that they had minimal effect on the results of the inverse dynamic analyses.

Kinematic data filtering was achieved in two ways, GCVQS and Butterworth filtering. In the first case the spline routine was used to interpolate and differentiate the scaled and rotated digitised coordinate data. One of the effects of the GCVQS is to overfit the data at times, and this tendency was highlighted clearly when points lay almost on a straight line, for example when the subject was standing still waiting to jump. The automatic spline routine tended to fit a high frequency low amplitude wave through or close to all the data points. The effect was to introduce what looked like additional noise into the the kinematic data. Therefore, although the data had in effect been smoothed by spline processing, an option to introduce a Butterworth filtering routine was also investigated. To tune the cutoff frequency to an optimum level for
each individual at each stage of the Marey jump, the vertical ground reaction force time data were offset from body weight and scaled by mass to produce acceleration-time traces which were used as a criterion against which to judge the influence of the Butterworth smoothing routine. The cutoff frequency was varied until the root mean square difference between the smoothed and differentiated mass centre acceleration was minimised with respect to the criterion. Data Padding was used to reduce the end point effects. Using the acceleration of the mass centre as the single point of interest within the subject's body, neglected the possible high frequency components in the kinematics which would have arisen at foot impact in particular. It was noticeable that the largest errors in acceleration were associated with toe and heel markers, and clearly for studies into segmental accelerations, shock absorption and force transmission through the body, then this form of low pass filtering should be avoided. The relatively high sampling frequency resulting from the use of the Hycam cine camera running at 250 Hz, meant that the advice offered by Lanshammer (1982) and by Kerwin and Chapman (1988) to collect position data at high rates even for what appear to be relatively low frequency activities was adhered to. However, the subsequent analysis of the influence of digitising at 1, 2 and 5 frame intervals, showed that the high rate was not required for the sorts of analyses being undertaken. The high sampling rate was however, beneficial in identifying critical instants in the Marey jump activity.

Fourier analysis of the force plate data, revealed that there were high frequency components in the actions being studied, but the signal energy within these components was very small and could be neglected. The high sampling frequency used for the force plate data capture of 2.5kHz was designed to overcome the possibility of aliasing arising from force plate resonances folding back into the signal spectrum. The purpose designed force plate mounting ensured resonances above 500 Hz and a software bi-linear digital filter was used to attenuate any components within the captured signal above 256 Hz. Synchronising the film and force data proved to be a challenge. The frame rate varied throughout the trials and the synchronisation device (stroboscope) did not produce a clean enough signal for the ADC sampling to be usable. Key times were therefore identified from the film and force traces to lock the two data sets together and then an interpolating cubic spline was used to match the film data to a precise 250 Hz frequency corresponding to every tenth force data point.

Segment angles, particularly the segments forming the knee joint and the representation of the trunk were investigated. Two markers at the knee had been used in the data capture, but the inverse dynamics analysis procedure requires the joint to be considered as as simple pin or hinge joint. The line of intersection between the two segments was used, but proved to be difficult to locate when the leg was close to full extension. A carefully placed single knee joint marker would probably have provided a more reliable digitising and analysis point and the two marker idea is not recommended. Defining the inclination of the trunk was also a problem. Bobbert et
al. (1986) used a point on the neck as the upper marker with the hip at the centre of rotation. The centre of the ear is also often used as a trunk landmark, but any extraneous head movements were likely to influence the trunk angle. Each subject's ear and shoulder centres were marked at data collection time and the mass centre of the trunk, including the head, neck and arms was determined. The latter point was used as the criterion point representing the upper marker for the trunk inclination angle. Analysis revealed that the head did move in flexion during landings and extension during takeoffs, whereas the level of agreement between the criterion (hip to HNT mass centre) and the hip to shoulder marker was very high throughout all phases of the jump. Although this was the preferred option for the current analyses, the use of the stylised jumping in an akimbo position meant that the shoulder marker was clearly visible throughout the action. This however, is not a general recommendation, since the shoulder centre is normally subject to circumduction and hence any surface markers are unlikely to be continuously visible.

Jumping for height

The major question at the start of this chapter concerned the possible benefits that could be gained by rebounding rather than performing a counter movement prior to vertical jumping. Many authors including Komi and Bosco (1978a) and Asmussen and Bonde-Peterson (1974a), who also cited Marey's observations, stated that rebound jumping enhanced the subsequent height gained in a vertical jump. The 'Marey' style of jump was chosen to mimic the Marey observation, and the ground reaction force data used to determine whether jump performances following a rebound were enhanced compared to a jump following a counter movement. The high sampling rate and correction for a non zero impulse at the end of the activity showed that takeoff velocity determined from time of flight and from integration were significantly different. To separately study takeoffs and landings the Marey jump was divided into six phases - two flights, two takeoffs and two landings. The differences between the time based and integration based methods for determining velocities were greater for the takeoffs (p<0.01) than for the landings (p<0.05). However, irrespective of the method chosen to determine the velocity at takeoff, there were no differences between the heights attained in the counter movement and the rebound jumps. There may have been a tendency by the subjects to hold back on the counter movement phase to ensure that they were in a good position to rebound for the second jump. Similarly there may have been a difficulty in landing from the first jump, if it had been a maximum effort, meaning that the rebound jump height could have been diminished. To check for these effects the jump performances reported in Chapter 3 were used for comparison. It was found that the subjects in the Marey jump study, attained higher jump heights in both phases of the Marey jump, than had been the case for subjects in the earlier study who had performed a counter movement and a drop jump as separate tasks. It was concluded that the subjects had become skilled in the Marey jumping task and had delivered maximum or near maximum efforts throughout the tests.
The first question had been answered. There appeared to be no evidence to support the idea that rebounding had enhanced subsequent jump height. This apparently contradicted the findings reported in Chapter 3. However, comparisons were not straightforward because the tasks, the subject groups and the resolution of the measurements used were different. Closer examination of the data highlighted that takeoff velocities in both studies were greater for the counter movement jumps than the drop jumps. In Chapter 3, stretch height at takeoff had not been examined and had been assumed to be consistent across each jump type, but the analysis in the current study had revealed that mass centre heights at takeoff were greater following a rebound than a counter movement. When the two heights, (stretch height and flight height) had been summed the differences in maximum jump height were eliminated. Comparisons with data from previously published research were re-examined because takeoff velocities only had been used to assess jump heights. Bedi et al., (1987) reported that jump heights attained using counter movement jumps were significantly greater (p<0.05) than those from any drop jumps (DJ25-DJ85 in steps of 10 cm). However, examination of the data revealed that the difference between the mean jump heights attained by the skilled jumpers (volleyball players) for the counter movement jump and the low drop jumps (DJ25 and DJ35) was 19 mm. Using the takeoff velocity data from the current study, a mean difference of 26 mm in favour of the counter movement jump was found. The difference in the mean stretch heights at takeoff was 22 mm in favour of the rebound jump. As a consequence the mean difference in maximum jump heights between the two takeoffs was 4 mm, which is almost identical to the precision with which mean jump heights can be predicted from force data sampled at 2.5 kHz, (±3 mm). It is therefore not surprising that the results showed no significant differences between the two types of jump. Applying a similar analysis to the other less skilled group of subjects (non-jumpers) in the Bedi et al., (1987) paper, the difference in jump heights (based on takeoff velocities) was 44 mm, and even allowing for possible differences in stretch heights, there was evidence to support the conclusion that counter movement jumps resulted in greater jump heights than drop jumps. Jump heights in the papers Komi and Bosco (1978a) and Asmussen and Bonde-Peterson (1974a) had also been calculated from takeoff velocities. The differences in jump heights were zero for the general student group and 23 mm for the skilled jumpers in the Komi and Bosco (1978a) paper. In the Asmussen and Bonde-Peterson (1974a) paper the corresponding mean difference was 10 mm. Bobbert et al., (1987a) used digitised cinefilm data to determine takeoff (stretch) heights, maximum jump heights and takeoff velocities. The mean difference in the height attained during the flight phases of the counter movement and drop jumps was small (~10 mm), with the equivalent difference in the maximum jump heights being 20 mm. No data were reported on the precision of measurement but the standard deviations for the group data were ±1 cm for takeoff height and ±6 cm for maximum height.

The differences in the skill levels of the subjects in all the studies which have been reviewed confounds the problem. Also when an effect size is so close to the precision of measurement,
and allowing for the improvements reported in Chapter 4, it is not difficult to realise why contradictory findings have been reported in the literature.

Comparisons between Takeoffs and Landings

There were secondary questions concerning the nature of the takeoffs and landings. In particular were different strategies adopted by the subjects to complete the two different takeoff and landing tasks? To answer these questions two approaches were taken. Initially the film data were used to study the kinematics of the jumps. This was followed by an inverse dynamics analysis in which the film and force plate data were combined. The kinematic analyses revealed that the two takeoffs were different. In takeoff one, from the bottom of the squat in the counter movement jump until loss of contact with the force plate, ($t_{of1}$) the takeoff velocity was higher than in the push off phase of the rebound jump, ($t_{of2}$). However, the stretch height at takeoff was lower in $t_{of1}$ than in $t_{of2}$. The net effect was that the jump heights in both actions were the same. Small differences in mass centre displacement and velocity at takeoff were evident. When segment angular motion was examined, the most striking aspect of the data was that the joint angular velocities for $t_{of2}$ appeared to be peaking or even increasing at the instant of takeoff. This is in contrast to the $t_{of1}$ plots, which were more typical of other velocity profiles for jumping, kicking and throwing (eg. Ingen Schenau et al. 1985; Robertson and Mosher 1985; Jöris, Muyen, Ingen Schenau and Kemper, 1985) with peaks occurring before the instant of takeoff. The rebound phase of the jump also appeared to enable the subjects to extend their legs more fully in the takeoff. Combining these two observations explained why the mass centre was higher in $t_{of2}$ than in $t_{of1}$. However, the drop in mass centre velocity in $t_{of2}$ was less expected. It might be anticipated that continuing to push against the ground through a greater range of motion would enable an athlete to apply force for longer and hence continue to accelerate the body. However, as Koning et al. (1987) have shown, the benefits gained by extending the leg beyond a certain point in the push off are minimal. The forces applied against the ground would be greater when the leg was more flexed (in $t_{of1}$) and therefore the impulse would be greater. It appears that the two takeoffs were slightly different. In $t_{of1}$ the leg does not appear to be able to extend as fully or as fast as in $t_{of2}$. However, the earlier departure from the ground before only the smallest muscles were propelling the body upwards, ensures a slightly higher, and possibly compensatory, takeoff velocity. Bobbert et al., (1987a) found the opposite concerning mass centre height at takeoff, reporting that that the mean height of the subjects' mass centres was 1 cm higher in the counter movement jump than for the bounce drop jump.

Surprisingly the peak forces at the three low squat positions, (ie. when the mass centre was at the bottom of either the counter movement, the rebound phase or the final landing), decreased throughout the action. The highest values were earliest in the Marey jump sequence. Also surprisingly, the time taken to descend from foot contact to the position when the mass centre
was at the bottom of the squat, was longer in the rebound phase than in the final landing. There were thus a number of small differences between the takeoff and landing actions. The landing prior to jumping required time over which to apply force both the bring the body to rest and to accelerate it up again as rapidly as possible. Extending the time over which a greater force could be applied is clearly beneficial, since the impulse and hence change in vertical linear momentum would be greater. In the final landing the task is to dissipate the vertical linear momentum, and so reducing the force and extending the time are clearly desirable. However, the time taken to arrive at the bottom of the squat was found to be shorter than in the rebound jump. The athletes may have been employing a different strategy. Perhaps they were sharing the work more evenly between the joints if the lower limbs. McNitt-Gray et al., (1993) showed that skilled gymnasts, when landing from varying heights, increased the contributions by the hip and ankle extensor moments to enable them to arrest the drop in a short time period. Recreational athletes used a deeper hip flexion and longer time period to achieve the same end. By using inverse dynamics, the resultant joint moment contributions and the associated muscle moment power and energy contributions could be used to further investigate differences between the two jumping and landing techniques.

Resultant or net joint moment has been defined as the sum of the moments developed by all muscles spanning a joint (Zajac and Gordon, 1989). Zatsiorsky and Latash (1993) make the point that joint moments have been referred to in biomechanics under many names, but they should be considered as fictitious and that in classical mechanics the term 'joint torque' is not defined or used. The concept of a net or resultant muscle or joint moment is however a very convenient way of examining contributions made by muscles acting around the joints. Zatsiorsky and Latash (1993) expand on the ideas put forward by Zajac and Gordon (1989) by including multi-joint muscles within the overall concept of a joint moment. By definition multi-joint muscles span and therefore have influence on more than a single joint and hence the need to accept that the net moment is a conceptual device rather than an entity. There are three inputs to the inverse dynamics analysis process, force, kinematic and inertia data. Using a force plate, the quality of the force data is well known, and bearing in mind the calibration information reported in Chapter 4, the level of uncertainty in any calculations could be stated. The other two inputs, inertia and kinematics are more prone to error and so the influences of fluctuations in these two input variables has been investigated. Ideally customised inertia data, specific to each individual subject could have been used. However, the subjects were young active sportsmen matching Zatsiorsky and Seluanov's (1983) sample, these data were selected. Winter's (1979) composite inertia data were used as a comparison set to investigate whether markedly differing results would arise as a consequence of variations in the inertia data alone. Challis and Kerwin (1996) used a systematic approach to quantifying the uncertainties in the determination of resultant joint moments of which variations in the inertia data and the computation of kinematic derivatives were two. The other four were related to the force and
kinematic data capture systems and the definition of joint centres and body axes. The focus of attention in the paper by Challis and Kerwin (1996) was evaluation of the level of errors arising from each contributing factor. In the current analysis, the actual values of the moments were not as important as the relative contributions made by each of the joints under two comparative conditions. Similarly, if the selected inertia data were not the most appropriate for the subjects and introduced systematic errors to the analyses, this would not be a major problem, providing that the relative contributions and strategies employed by each subject did not depend on the inertia data selected. The computation of derivatives is dependent on the amount and nature of the data smoothing that is employed. The spline processes used inevitably introduced some smoothing within the interpolation processes. However, these data were treated as 'Raw' data for the purposes of investigating the influence of a Butterworth filter.

Andrews (1983) reviewed a number of measures of muscular effort and suggested that scalar angular impulse was attractive because it could be applied across a wide range of activities and was meaningful during eccentric, isometric and concentric muscular activity. He did however, warn against trying to treat this as a vector quantity for determining changes in segmental angular momenta.

Alexander and Vernon's (1975) quasi-static approximation to muscle moments was very attractive for its simplicity and was not dependent on inertia data or derivatives. However, Winter (1990) has strongly criticised this technique as potentially misleading. Wells (1981) on the other hand, showed it to be a useful technique. Once again, if the relative contributions made by the joints was unchanged when using this simple method, then it could be effective in examining inter- and intra-subject variability in jumping and landing tasks in the future.

The resultant muscle moments were calculated with one inertia data set ('Z') and with the Butterworth filtered kinematic data. A series of comparisons were made concerning the relative magnitude and timing of the muscle moment peaks for each joint in the two takeoffs and landings. These moment values were combined with joint relative angular velocities and time durations to determine muscle moment power and angular impulse. The power time histories were integrated to determine muscle moment work at each phase of the action. The inverse dynamics data for one subject (CJP) were removed from the analyses because they were obviously incorrect, but the reason for these errors could not be found.

The muscle moment data were normalised with respect to body weight and leg length and the time axis was normalised with 0% at the bottom of the squat and 100% at takeoff. For the landings this was reversed with 0% being coincident with impact. The general trend of peaking in the proximal to distal order for both takeoffs was evident, and is in agreement with other published examples (Bobbert and Ingen Schenau, 1988). However, all the peaks were later in
tof₂ than tof₁, indicating that the two takeoffs were different. The peak moments in ldg₂ were greater than those in ldg₁. However, based on the observation that the time to come to rest at the bottom of the squat was shorter in ldg₂ than in ldg₁, larger muscle moments were anticipated. There was no obvious pattern in the timing of the peaks for the landings. This is also in agreement with for example Sanders and Allen (1993) and McNitt-Gray et al., (1993). Both groups investigated subjects dropping onto variable compliant surfaces and found that the ordering of the muscle moment peaks varied from surface to surface and from person to person. In a study of the muscle moments in jogging Winter (1983) reported that subjects produced a normalised support moments of similar magnitudes, but that the contributions from each of the joints varied considerably. There is conflicting evidence about the effectiveness of bounce jumping compared to counter movement jumping. Bobbert et al., (1987a) reported a study comparing a counter movement vertical jump and two types of low drop jumps and found that all three jumps resulted in very similar takeoff velocities. Komi and Bosco, (1978a) and Hakkinen and Komi, (1983) found that that drop jumps produced greater jump heights than counter movement jumps, but they didn't specifically report takeoff velocities. Other studies of jumping have considered squat and counter movement rather than counter and drop jump actions and found differences in favour of the counter movement technique in terms of forces, power and external work, (Bosco and Komi, 1981; Fukashiro et al., 1983). These authors suggested that any pre-stretching of the extensor muscles produced enhanced jumping performance. This was not the case in the current research. Bobbert et al., (1987a) found that the moments and power output at the ankle and knee joints were greatest in the bounce drop jump technique but the greatest hip moments occurred in the counter movement jump but advised that the precise nature of the drop jump action should be controlled to encourage the 'bounce' style. In the follow up paper to this study, Bobbert et al., (1987b) extended the 'bounce' drop jump to study the influence of increasing the heights of dropping and thereby increased stretch loading on the extensor muscle groups of the lower limbs. Using similar calculations they found no differences in joint power output for the push off phases from the three drop heights.

Integration of the power time histories in the current study was carried out from the bottom of the squat to takeoff and from impact to the bottom of the squat and were determined to quantify the net muscle work being contributed by each joint. All four subjects retained the general pattern of work at the joints for tof₂ that they used in tof₁. One subject increased the contribution by the knees, two increased the contribution from the hips, and one reproduced virtually the same pattern in both takeoffs. In the landings three subjects used a knee dominated strategy in ldg₁, and two subjects used an ankle dominated strategy in ldg₂. Of the two subjects who retained a knee dominated strategy in both landings, one increased the contribution from the knees in ldg₂ compared to ldg₁, whereas the other retained the same pattern by sharing the work between the three joints. One subject (AAC) changed from a knee dominated approach in ldg₁
to an ankle and hip dominated strategy in \( \text{ldg}_2 \). The average normalised work in \( \text{tof}_1 \) was the same as that in \( \text{tof}_2 \), whereas the mean normalised work in \( \text{ldg}_1 \) was about 15% greater than that for \( \text{ldg}_2 \). There was no evidence of an overall strategy for the subjects.

By comparing the jumping performance of ten volleyball and ten handball players executing vertical jump takeoffs Bobbert and Ingen Schenau (1987) hoped to determine factors which distinguished good jumping technique from poorer technique. They found that that volleyball players jumped on average 11 cm higher after takeoff than the handball players and attributed this largely to a smaller hip angle at the start of the push off phase and hence a greater time and distance over which to apply force. They were unable to determine whether the greater performance was due to differences in power output capacity or improved coordination.

The total support angular impulse values were either the same or greater for \( \text{tof}_1 \) than for \( \text{tof}_2 \). The angular impulses for the landings reflected similar distributions between the three joints with the mean values being identical in both cases. Individual trials did not reflect this consistency and so again there did not appear to be a clear pattern emerging.

The investigations into the influences of different inertia data, and digital filtering of the kinematic data produced no changes in the findings and so were not pursed any further. All the graphs summarising these data have been included in Appendices 5.7 and 5.8.

The quasi-static technique, favoured by Alexander and Vernon (1975), Wells (1981) and Watkins and Nicol (1986) but despised by Winter (1990) produced interesting results. The resultant muscle moments at the ankles agreed to within 1% (RMSD) with the inverse dynamics data. The corresponding values at the knees and hips were close to 5% and 15% respectively. The overall support moments were between 6% and 10% greater than the inverse dynamics values for the same input data. All quasi-static values were greater than the inverse dynamics counterparts. However, the interesting aspect of this part of the analysis was that the discrepancies were greatest in the takeoffs and least in the landings. As the quasi-static technique ignores inertia forces, this appears to be opposite to the expected result. This observation may in part be explained by the filtering processes which attenuated the frequencies in the range of 5 Hz to 12 Hz depending on the phase of the movement being studied. The force data were filtered at 256 Hz and so would not have been unduly effected since the highest frequency components of significant signal energy were well below 50 Hz. These force data were used in both analyses, but the differentiated version of the smoothed positional data were only present in the inverse dynamics analyses.
5.5 SUMMARY

The purpose of this analysis was to determine whether jump heights following a rebound were greater than those following a counter movement. Force, cinefilm and segmental inertia data were combined in a study of counter movement and rebound jumping. High sampling rates were used to identify key moments in time for synchronisation purposes and to accurately define flight times. Takeoff velocities were determined from flight times and from integration with and without correction factors. It was found that, irrespective of the method of analysis chosen, the jump heights attained from a counter movement and a rebound were the same. The methods by which these heights were attained varied. In the counter movement jump the takeoff velocity of the mass centre was slightly higher than in the rebound jump but the stretch height of the mass centre at takeoff was lower. In the push off phase from the bottom of the squat to takeoff, the leg extension and extension angular velocity were greater in the rebound jump than in the counter movement jump. Inverse dynamics analyses were used to quantify resultant muscle moments, muscle moment power and energy, and also to determine scalar angular impulse values. The influence of two sets of inertia data, and digital data filtering prior to differentiation, on the resultant moments was shown not to alter the overall findings. Quasi-static techniques were investigated and shown to consistently over estimate the resultant muscle moments. Agreement between the two sets of moments was close at the ankles and knees. At the hips, the errors were large enough to alter the relative contributions being made by the joints and hence to invalidate this method of analysing vertical jumping. There were no clear differences between the two takeoffs and landings and there was evidence to indicate that different strategies were adopted by individuals to solve the force and work requirements of these two similar but slightly different takeoffs and landings.
CHAPTER 6

SUMMARY AND GENERAL DISCUSSION

6:1 INTRODUCTION

Vertical jumping is of interest in training for sport, as a model for experimental investigations of elastic energy and as an ideal movement skill for simulation modelling and optimisation studies. Plyometrics is a form of strength training in which athletes drop from a raised platform and rebound from the floor in an attempt to "stretch load" the leg extensor muscles and increase jumping performance. It has been adopted as a valuable part of a training programme for athletic events like long and high jump and in games like volleyball and basketball where jumping is paramount. Coaching booklets (Radcliffe and Farentinos, 1985) and articles have been written which explain the benefits of this form of training and outline training programmes in terms of numbers of repetitions and frequency of training. There is some practical evidence that plyometric training produces results, but the mechanisms behind the jumping action itself are not well understood. Blimkie (1979) along with many other practitioners, (Costello, 1984; Miller and Power, 1981; Moynihan, 1983; Polhemus, 1981; Steben and Steben, 1981; Verhoshanski, 1968 and Wilt, 1978), reported that pre-stretching increases the force of a shortening muscle contraction and that muscles have elastic properties which can store and transfer energy. Blimkie (1979) also claimed that this ability to store and transfer energy could be improved with training. The whole practice of plyometric training is based on these ideas. Komi et al., (1978a) stated that the optimum dropping height was ~65 cm, but Bobbert, et al., (1987b) showed that heights above about 40 cm were more likely to cause injury to the athlete without any improvements in stretch loading attributable to a drop jumping exercise regime. An article in the Soviet Sports Review (Dursenev and Raevsky, 1979), recommended drop jumping from heights up to 3.2 m. They concluded that the most effective stimulation of the muscles could be achieved from the highest drop heights. They had tested athletes from three dropping heights and concluded that the increased benefits over the group dropping from the lower heights of 0.75 m to 1.10 m were substantial. The peak forces recorded during the drops from the highest platforms were in excess of 20 times body weight and the report included some worrying comments concerning the fact that the subjects working from the highest drop heights did so "without desire" and "sometimes under pressure from the instructor" highlight the perceived dangers of this type of activity. When the observations by Bobbert et al., (1987b) advising drop heights to be limited to 40 cm, and bearing in mind ethical considerations, it is not surprising that this extreme form of plyometric training has not been widely recommended to western athletes.
The research in this thesis has examined some of the conflicting evidence associated with plyometric jumping activities and developed data capture and analysis procedures which have been employed to study vertical jumping with varying amounts of pre-stretching. Inverse dynamic analyses have also been used to investigate individual strategies employed by a group of jumpers in an attempt to gain insight into the mechanisms employed to optimise vertical jump performances whilst avoiding injury.

6:2 LIMITATIONS

Limitations within the study were inevitable, but care was taken throughout to minimise errors. The total number of subjects (14 in the first study and 8 in the second) was relatively small, but the use of repeated trials enabled checks on consistency of force plate data to be conducted and provided confidence in the consistency of the movements being studied. Filming only one of six trials for the inverse dynamics analyses was a problem, arising mostly from the limitations of the data collection and analysis technology used. It would have been preferable to obtain kinematic data, with synchronised force plate data, on all trials. (An independent study of a single subject performing five counter movement jump takeoffs has shown that peak moment variability in ankle, knee, hip and support values between trials was less than 5%, and that the timing of the peak values agreed to within 3% of the takeoff period and always followed the same sequence). A great deal of time and effort was consumed in developing the equipment, interfaces and computer software to enable the analyses to be undertaken. If this study were to be repeated, a modern automatic movement analysis system could be used for overcome many of these problems and allow the time to have been used more effectively. Variations in the skill levels of the subjects in this, and other studies, has been a confounding factor. The selection of well trained young adults reduced the possible influence of skill in the current study but limited comparisons with the findings of other studies.

6:3 SUMMARY

This research began as an attempt to clarify discrepancies in findings on vertical jumping. Evidence from the literature suggested that squat jumping, counter movement jumping and rebound jumping each resulted in increasing vertical jump heights. The arguments put forward centred upon two ideas. Pre-stretching a muscle to provide better mechanical conditions for contraction and pre-stretching a muscle-tendon unit to accumulate elastic energy for subsequent recovery. Early studies (eg. Davies and Rennie, 1968; Asmussen and Bonde-Peterson, 1974a; Komi and Bosco. 1978a) showed that stretch loading the extensor muscles enhanced jumping performance, and that within reasonable limits, increasing the stretch loading increased the resulting jumping performance. Komi and Bosco (1978a) reported that subjects achieved the greatest jump heights when dropping from "optimum" heights of around 0.65 m for males and
0.48 m for females. In contrast Cavagna, et al., (1971) reported data for squat jumping, counter movement jumping and rebound jumping in which no apparent improvements in jump heights could be observed. Bedi et al., (1987) also opposed Komi and Bosco's (1978) findings when they reported that counter movement jumps resulted in significantly better performances than any of the drop jumps investigated. Bedi et al., (1987) also stated that there were no significant differences between the jump heights attained from any drop height.

The earliest studies used chart recorders to obtain force plate data and, in Asmussen and Bonde-Peterson's (1974a, b) case, used a low frequency force plate to obtain the data. Bedi et al., (1987) used a substantial ANOVA rather than descriptive analyses or 't' tests which had been reported by the other research groups. It became clear that some of the discrepancies in findings may have arisen, at least in part, as a result of data which were not precise enough to detect the small differences in time and force associated with these jumping activities. The development of equipment, calculation procedures and computer software was required to improve precision before progress could be made to account for the reported discrepancies.

The first study, reported in Chapter 3, repeated the protocols of Komi and Bosco (1978a, b) with two exceptions. The flight times were precisely measured using a computerised force capture system and none of the "drop" heights were regarded as the heights of the platform from which the subjects began. A true drop height was calculated from the ground contact impulse and the flight time following the rebound jump.

Squat, counter movement and drop jumping tasks were undertaken to examine the influence of the stretch-shortening cycle on jump performance. Enhanced time resolution was attained through the use of a computerised force data capture system. The results from the initial squat and counter movement jump trials indicated that by sampling data at 500 Hz the height of a single jump could be determined, by integration of the force trace, with a confidence interval of ±0.03 m. (The standard error was approximately ±5 mm). Also it was determined that over 90% of the variability in jump height could be accounted for by flight time. This information was used in the following drop jumping study. Male and female subjects performed a series of drop jumps from platforms increasing in height by 0.15 m up to a maximum of 0.90 m. The zero height condition corresponded to a counter movement jump.

All the jumps following a counter movement or drop jump resulted in jump heights which were greater than the heights achieved from a squat jump. Males improved by 25% and females by 11%. This was the reverse of the finding by Komi and Bosco (1978a). In addition they reported that the specialist male jumpers (volley ball players) in Komi and Bosco's (1978a) study jumped higher than the other males in the study. The females in the Komi and Bosco (1978a) study jumped consistently lower than the females in the current study. It therefore appeared that the
skill level of the subjects was an important factor contributing to the variability in the findings. The current analysis also revealed that no optimal drop height, identified by Komi and Bosco (1978a), could be found. Some subjects rebounded better from a low starting point and some from a high starting point. The group response was almost flat, with similar "stretch loading" enhancements being seen with drops ranging from 0.10 m to 0.70 m.

This study highlighted the very small differences in flight times and force impulses that had to be detected for this form of analysis. Before progressing to a more comprehensive study of jumping which included cinefilm and force data, a new mounting for the force plate had to be built and a new system of computer hardware and software introduced to replace the original data capture system which no longer functioned. Chapter 4 reports a series of experiments which were designed to establish the accuracy of force plate and visual recording procedures which were to be used. Initially the frequency characteristics of the force plate and its newly designed laboratory mounting were evaluated. Static and dynamic accuracy tests of the force plate followed. Secondly, the measurement accuracy of two different visual recording and digitising systems were determined.

The redesign of the force plate mounting and modal analysis of the combined force plate and support structure together with independent frequency analysis of human movement indicated that a sampling frequency of 2.5 kHz was required. A software digital filter was employed to eliminate plate resonances whilst maintaining signal fidelity. Vertical force errors averaged 0.1% and the point of force application errors near the centre of the plate were close to the manufacturer's claimed figure of ±2 mm. Errors at the corners of the plate were up to three times larger. The increase in data volume arising from the long duration of the Marey style jumping action required additional software.

A calibration plane with 35 control points was used to determine accuracy of two visual analysis systems. Images recorded with a 16 mm cine-film camera and a CCD video camera and sVHS video recorder were analysed using a tablet digitiser and video frame store respectively. Although both cine-film and video were capable of providing the required sampling rate, the markedly superior measurement accuracy of the cine-film based system made this the preferred option for the 'Marey' jump study. Based on the results of the calibration study, image offset, scaling and rotation factors were calculated from repeated digitisations of nine well spaced control points. Worthwhile improvements in accuracy could be obtained by correcting images for relatively small camera/projector roll errors. In an image field width of 2 m the expected root mean square errors between image points and criterion data points was on average 2.4 mm across the total field and well defined points were accurate to ±5 mm.

In Chapter 5, the force plate and image analysis systems defined in Chapter 4, were used to
collect data on eight male subjects for a detailed study of jumping. A combination of a counter movement jump and an immediate rebound jump and landing, termed a Marey jump, was used as the experimental task to determine whether jump heights following a rebound were greater than those following a counter movement. Body segment inertia parameters based on two sources were used in the subsequent inverse dynamics analyses. Analysis of the cinefilm revealed that frame rates varied throughout the trials. Spline interpolated film data were synchronised onto the corresponding force data time base. Butterworth digital filtering, with end point "padding", was used to reduce the influence of digitisation errors on linear and angular accelerations. Cutoff frequencies were individually selected for each subject at each phase of the Marey jump by minimising the root mean squared differences between mass centre acceleration time histories derived from cinefilm and force plate data. The mass centre of a single segment encompassing the head, neck, trunk and arms was used as the criterion end point in defining the trunk segment. Trunk angles were found to be reliably defined by a line from the hip to the shoulder. Leg extension was more complete and leg extension angular velocities were larger and peaked later in rebound jump takeoffs than in counter movement jump takeoffs.

Integration of force plate data, which had been used in Chapter 3, was extended in three ways. The sampling frequency was increased by a factor of five to 2.5kHz. A correction based on a non zero terminal linear momentum was included and the statistical analyses were extended to examine trial order effects. Overall jump heights attained following a counter movement and a rebound were found to be the same. This apparently contradicted the findings of Bedi et al., (1987) and also those reported in Chapter 3. However, both studies (Chapter 3 and Chapter 5) found that takeoff velocity in the counter movement jump exceeded that in the rebound jump. Stretch height at takeoff had not been investigated in the earlier studies (Bedi et al., 1987; Komi and Bosco, 1978a; Asmussen and Bonde-Peterson, 1974a). In Chapter 5, stretch heights were added to flight heights and then the differences between the maximum heights attained by the two different jump takeoffs were virtually eliminated and so the conclusion that there were no differences in jump performances was valid and did not contradict the findings from Chapter 3.

There were two takeoffs (tof₁ and tof₂) and two landings (ldg₁ and ldg₂) in each Marey jump. Inverse dynamics analyses were added to the kinematic and force data integration studies to investigate possible differences between takeoffs following counter movement and rebound jumps, and also between landings either preceding rebounding or prior to coming to rest. The influences of two sets of inertia data, and digital data filtering prior to differentiation, on the resultant moments were shown not to alter the overall findings. Detailed data on five subjects were used to investigate the contributions made by the joints of the lower limbs in the two takeoff and two landing actions. Resultant muscle moments, muscle moment power and muscle moment energy were used to investigate differences in the patterns of motion used by the subjects to solve the load sharing problems. Also scalar angular impulse values, as described by
Andrews (1983), were determined as an alternative method of quantifying the contributions made by the muscle moments. Quasi-static techniques, as advocated by Alexander and Vernon (1975a), were compared with the criterion data generated using inverse dynamics.

The mean time to complete tof$_1$ was shorter than for tof$_2$, but there was considerable subject variability. The time taken for ldg$_1$ was longer than for ldg$_2$ (p<0.01). Also the depth of squat in ldg$_1$ was greater than for ldg$_2$. The average vertical forces in tof$_1$ and tof$_2$ were the same, but the peak vertical force at the lowest point of the squat decreased throughout the Marey jump sequence with the greatest being in the counter movement and the least in the final landing.

Muscle moment data were normalised to facilitate inter-subject comparisons. Each moment value was divided by subject mass and leg length and interpolated onto a 0%-100% time axis. The assumption was made that both legs shared the force production equally. Lower limb support moments, as defined by Winter (1980), were calculated as the sum of the extensor moments at the ankles, knees and hips. The muscle moment data for one subject were removed from the analysis as no explanation could be found to account for the apparent anomalies present. The phasing of the peak muscle moments in takeoffs followed a general proximal to distal sequence in both takeoffs, but the peaks were consistently later in tof$_2$. The peak moments in ldg$_2$ were greater than those in ldg$_1$. Larger moments might have been expected to meet the need to rebound rather than to come to rest, but as the time taken in ldg$_1$ was greater than that for ldg$_2$ it was not surprising that the moments were lower. There did not appear to by any particular pattern to the peaking of the landing moments in the two landings, which is in agreement with the relatively recent observations by Sanders and Allen (1993) and McNitt-Gray et al., (1993). Both these studies focussed on muscle moment strategies when landing on variable compliant surfaces.

The muscle moment time histories were multiplied by the corresponding relative angular velocities at each joint to determine the muscle moment power in each phase of the Marey jump. The power time curves were integrated with respect to time to determine the eccentric and concentric work contributed by each joint. The data were normalised to W.kg$^{-1}$ and J.kg$^{-1}$ using body mass, and interpolated over a 0%-100% time scale. The work sharing pattern in the two takeoffs remained constant with each joint making a similar contribution in both actions. The general pattern in ldg$_1$ was dominated by the knee extensors, whereas the ankles and hips appeared to be more dominant in ldg$_2$. The mean muscle moment work in ldg$_1$ was 15% greater than in ldg$_2$.

Angular impulse was determined by integrating the muscle moment data with respect to time. These scalar angular impulse values were used as an alternative representation of the contribution made by each joint to each part of the action. Andrews (1983) suggested that this
was a useful concept since it could be generally applied to eccentric, isometric and concentric muscle activity, but did warn against using these data to imply any changes in limb angular momenta. Support angular impulse values tended to be the same or slightly greater for toff₁ than toff₂. The sharing of the joint contributions remained similar in both takeoffs and landings with the knees being dominant during takeoffs and the ankles being dominant during landings.

Quasi-static techniques for calculating muscle moments were developed from the work presented by Alexander and Vernon (1975a). The lower limb support moments were between 6% to 10% greater than the equivalent values obtained with inverse dynamics. Root mean squared differences between quasi-static and inverse dynamic moments were calculated. Agreement between the two sets of moments was close at the ankles (1%) and knees (5%). At the hips, the errors (15%) were large enough to alter the relative contributions being made by the joints and hence to invalidate this method for analysing hip contributions in vertical jumping.

The research has explained some of the reasons why conflicting evidence associated with vertical jumping activities has arisen. It has also investigated mechanisms underlying jumping techniques by examining takeoffs and landings which have different purposes. The research has also examined individual responses by subjects wishing to achieve a common objective and in so doing has highlighted a variability which makes the task of explaining the underlying mechanisms of movement coordination and power production difficult to determine by purely experimental means. Modelling is a method which offers another insight into these problems.

6:4 THE FUTURE

Hay et al. (1978), argued that the jumping actions described by Komi and his co-workers were far from "simple" and that an improved understanding of two segment motions was required before the complexity of jumping could be investigated with any confidence. Alexander (1990) used a very simple two segment model of a human to investigate strategies in jump takeoffs. The model comprised two massless leg segments, a point mass centre at the hip and a single muscle representation at the "knee" joint. Despite its simplicity it was able to predict optimum approach velocities and plant angles for high and long jump takeoffs. It was not sophisticated enough to be used to simulate individual performances but the underlying mechanisms and explanations of why approach velocities in high jumping are optimal at around 7.5 m.s⁻¹ to 8 m.s⁻¹ were clearly demonstrated. In another paper (Alexander, 1991) detailed a two muscle, jointed link model of throwing to investigate muscle coordination. Once again the essence of the skill of throwing, that is to produce maximum release velocity at the appropriate time, was accurately predicted and explained. Alexander (1992a) argued strongly in favour of simple models saying that they were useful in identifying basic principles and in discovering the
features within a movement which give rise to the observed effects.

At the other end of the spectrum, models have been developed to account for the complexities of muscular contraction, (eg. Winters, 1990). Models of this nature attempt to represent the chemical changes and interactions which bring about the typical force-length-velocity profiles when combined with serial tendons. Between these two extremes lie models which include a four link planar representation of the human skeletal system with frictionless pin joints driven by theoretical force actuators. Models of this type include those by Bobbert et al. (1986) and Pandy et al., (1990) and have been used extensively in the study of vertical jumping, (eg. Bobbert and Ingen Schenau, 1988; Bobbert and Soest, 1994; Pandy and Zajac, 1991). These models employ "bang-bang" control to stimulate Hill type modelled muscles which comprise a force actuator, series elastic component and parallel elastic component. The number of muscle groups surrounding the ankles, knees and hips which have been included in the models has varied from six to eight, but in most aspects the models are very similar.

Vertical jumping has been a central theme in the development of simulation models in human movement. One if the greatest attractions is the fact that the optimisation criterion (maximum rise of the mass centre) can be readily defined. The performance of the model can be evaluated against experimentally determined data. For example Anderson and Pandy (1993) used muscle activation patterns (EMG), body segmental motions, ground reaction forces, jump height and total ground contact time to evaluate the model within a study of squat and counter movement jumping.

Since the mid 1980's two research groups, one working in Europe (Amsterdam) and the other in the USA (Stanford) have investigated a variety of aspects of jumping including the role of bi-articular muscles and the storage and utilisation of elastic energy. The Amsterdam team believe that the major role for bi-articular muscles is the radial transport of power, whilst the Stanford group favour coordination as the vital contribution. Pandy and Zajac (1991) challenged the bi-articular contribution by changing the gastrocnemius from a bi-articular to a mono-articular muscle within their model. They were able to investigate the role of the plantar flexors and found no differences in jumping performance between the two conditions. They did acknowledge that the plantar flexors were very important in power production, increasing jumping height be as much as 25%, but they did not agree that the power contribution arose due to the bi-articularity of the gastrocnemius. This contradicts the theory put forward by Ingen Schenau and colleagues. In a very recent study Jacobs, Bobbert and Ingen Schenau (1996) reported mechanical output from individual muscles during jumping and sprint starting. Their main finding was that bi-articular leg muscles contributed significantly to the work done at the joints, due to transfer of power during explosive leg extensions.
Soest and Bobbert (1994) reported a study on vertical jumping in which customised strength and segmental limb lengths data were obtained on a series of subjects. Cinefilm, force plate and EMG records of the subjects performing vertical jumps were also obtained. A simulation model (Bobbert et al., 1986) was used to replicate these jumping performances. Once evaluation had been completed, muscle strength and muscle activation patterns were altered to investigate the relative importance of each contributing factor to the overall jumping performance. Extremely small changes in the activation patterns of muscle stimulation were sufficient to destroy the integrity of the skill. The model extended the legs, but the timing of the stimulation pattern was highly sensitive and critical in controlling the direction of the jump. Ingen Schenau and Soest (1994) also noted that in vertical jumping, the body acts as an inverted pendulum structure and the magnitude and direction of the foot reaction forces have to be controlled with high accuracy to preserve equilibrium and to optimise external work output. Appendix 5.10 contains a vector graphic sequence for one of the subjects performing a rebound jump taken from the current research. The graphic contains images from an animation sequence and shows how the direction of the force vector changes four times in four consecutive images (0.08 s). Rapid changes might be anticipated in an impact, but the horizontal forces plotted in Figure 5.20 and Appendix 5.11, also show rapid changes of direction in the horizontal force component just prior to takeoff in the counter movement jump. The control strategies necessary to facilitate these rapid changes are clearly well established in skilled movement, but are not yet understood. Ingen Schenau (1994) proposed that the control of maximal force leg extension activities like jumping exhibit a pattern of movement in which the angular momentum of the body during the driving phase is maintained as close to zero as possible. He suggested that this was the controlling strategy that exemplified these rapid and forceful extension skills. Here is an area for future research. Anderson and Pandy (1993) used a newer version of the Pandy et al. (1990) model with more sophisticated muscle activation than bang-bang control. This addition enabled the eccentric phase of a counter movement to be modelled more fully. As a result they challenged many of the ideas which have been accepted by a range of scientists about the contribution of elastic energy in jumping. In particular they showed that more elastic energy was lost as heat in the counter movement jump than the squat jump. The authors acknowledged that the counter movement might result in a slightly better jumping performance than could be achieved from a squat jump, but they found that jump heights attained in both types of jump were almost identical and concluded that elastic energy enhanced jumping efficiency rather than jump height performance.

These examples highlight a great strength of the modelling approach. The control provided by a simulation model is illustrated by the ability to change the stimulation to the muscles or to move the origin of a muscle group and then to run the model again to investigate the changes that occur. In the study of human movement this is a rare and powerful position to be in. The scientist is provided with an ideal experimental environment where all other variables can be
maintained whilst the test variable is manipulated independently. Interventions of this nature are very difficult to reproduce in an experimental study. The conflict between the findings of the two separate research groups also exemplifies one of the great weaknesses of simulation modelling studies. A model may lack agreement with reality. A model is an abstraction of a physical system and as such the results of model simulations should be considered accordingly. Perhaps the fact that these two research groups have been working on these jumping models for over ten years now and are beginning to agree about some findings, for example about the differences in jump height attainable with and without a counter movement, is a reflection of the developments of their respective models rather than one of a basic change in either group's theoretical standpoint.

Experimental and simulation studies both have a role to play in the future analyses of human movement. The mechanics of vertical jumping has proved to be a challenge to both these methods of investigation with contradictory findings arising from both sources. Recent developments in computerised data capture and analysis systems (e.g. CODAmpx30, Vicon 370, MacReflex) facilitates the study of larger groups of subjects with more trials per subject and with greater precision per trial. Anderson and Pandy (1993), although describing a simulation study, acknowledged the reliance of modellers on experimental data for evaluative purposes. They also commented on the lack of precision which had undermined many experimental studies in the past. Even with modern equipment they were unable to determine jumps heights with sufficient accuracy to be able to detect the very small effect size that they had observed through simulation. Improvements in inertia data based on CT and MRI scans together with virtual imagery from projects like the "Visible Human" now available on the Internet, mean that improved representations of individual subjects will be more readily available. More powerful computers and improvements in muscle and skeletal modelling algorithms will enable greater insight into the complexities of muscle coordination and force production to be gained. Simulation offers the ability to determine energy transfers within the body via individual muscles rather than relying on the "fictitious" muscle moments as discussed by Zatsiorsky and Latash (1993). Prilutsky and Zatsiorsky (1994) extended inverse dynamics by estimating muscle lengths and hence velocities and forces to determine intersegmental energy exchanges. They also evaluated the energy transferred through bi-articular muscles by finding the difference between the time integral of the power generated by the moment and total power of the muscles serving the joint. These analyses depended on a series of approximations based on cadavaric data and joint angles to determine muscle lengths.

Future work to extend inverse dynamics linked with new insights from forward dynamics open opportunities for the future which will hopefully clarify a number of the unresolved issues present in current research literature.
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219-233.


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Contribution to the proceedings of the 3e Symposium International de biologie de l'exercice et
de l'entraînement physique, Nice. (Personal communication).


APPENDIX A - DATA

Appendix A contains additional tables, and figures to supplement the results in Chapters 3, 4 and 5.

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Appendix 3.1 Vertical Jump data

(time v integration takeoff velocity)

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- **St.Dev**: 0.27
- **Variance**: 0.07
- **Coeff of V**: 0.12
- **Coeff of V**: 0.14
Appendix 3.2 (a-f) CMJ, SJ and DJ 0.15-0.90 Jump Height Data

3.2a Male Data Series 1, Jump height (m) calculated from flight time following Counter Movement Jumps and Squat Jumps

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3.2b Female Data Series 1, Jump height (m) calculated from flight time following Counter Movement Jumps and Squat Jumps

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3.2c. Male Data Series 2, Jump Height (m) from flight time following Drop Jumps from Nominal Drop Heights of 0.15 m to 0.90 m. (test 1)

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### 3.2f Female Data Series 2, Jump height (m) calculated from flight time following Drop Jumps from Nominal Drop Heights of 0.15 m to 0.90 m. (test 2)

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*.* = missing data point
Appendix 4.1. Force Plate Calibration

(a) Vertical Force Data (Fz)

Linear Regression forced through the origin. All data corrected for zero offset based on force plate output of 7.88 N for zero loading.
Correlation Coefficient = 0.999997 (Adjusted 0.999996)
Prediction accuracy using regression equation at 99% Confidence Interval for individual data points:
- 500 N: 490 - 509 N
- 1000 N: 988 - 1007 N
Linearity of Force Plate supported.
Accuracy of the Force Plate claimed at <1% supported. Static Loading accuracy in 1400 N range found to be approximately 0.2% (99% Confidence Interval).
(Amplifiers set to 5000 N = ±10V DC)

(b) Static Point of Force Loading

Point loads of approximately 500 N were applied at the corner points (solid black circles), at the centres of the midline (grey circles) and at the origin of the plate (0,0)

The RMS difference between the actual location and the force plate output location was computed for each point. The means and standard deviations for the corner points and the mid line points were calculated.

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<th>Mid Line Points</th>
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FORCE PLATE OUTPUT (N)

CALIBRATION FORCE (N)
Appendix 4.2. Modal Analysis of Force Plate and Mounting

(a) Modal Analysis: Imaginary components of transfer function for force plate mounted in the athletics stadium track, (Condition C).

In both illustrations (a and b) data for impacts across half the plate surface have been included, (ie X ranging from -200 mm to +200 mm, Y ranging from 0 mm to +300 mm).
Note the lack of resonances below 800 Hz and the prominent resonances at 860 and 1125 Hz.

(a) Modal Analysis: Imaginary components of transfer function for force plate mounted in the laboratory (Condition B, machine tool base plate).

Note the large number of resonances for this surface mounting. Frequencies ranged from 520 to 1940 Hz with many more mode shapes evident than for the track mounting shown in (a).
Appendix 4.3 (35 Point Digitising Criterion Data Set)

Criterion data set (7 columns of 5 rows of points @ 19.5 cm centres)
Origin in column 4 row 3

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Appendix 5.1. Digitising Reference Frame ("X" Tree Data)

CRITERION DATA (m)

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<th>C2Y</th>
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DIGITISED DATA (mm)

Film Roll #0

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Film Roll #1

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Appendix 5.2a. (i). Photographs of subjects AAC, DDA, GCG, AKS and CJP showing the digitising markings. (A4 prints of these images were digitised to obtain the lengths required to convert the Zatsiorsky data into a format comparable with the Winter data).
Appendix 5.2a. (ii). Photograph of subject DJS showing the digitising and 4 control points. (A4 prints of these images were digitised to obtain the lengths required to convert the Zatsiorsky data into a format comparable with the Winter data).
Appendix 5.2b. Inertia Data calculations based on 35 mm photographic images.

Reference: Zatsiorsky and Seluanov (1983)

Moment of inertia of a segment about a tranverse axis through the proximal end ($I_p$) for a segment of length ($l$) and mass ($m$), with radius of gyration ($K$), proximal radius of gyration ratio ($k_p$) and proximal mass centre ratio ($r_p$) is given by the equations:

\[ I_p = I_{cm} + m \cdot d^2 \]
\[ d = l \cdot r_p \]
\[ I_p = m \cdot k_p^2 \]
\[ K = l \cdot k_p \]
\[ I_{cm} = m \cdot l^2 \cdot (k_p^2 - r_p^2) \]

The radius of gyration ratio with respect to the mass centre location ($k_c$) is then given by equation:

\[ k_c = \frac{1}{l} \sqrt{\frac{T}{m}} \]  \hspace{1cm} (1)

Using equation (1) and the data for five subjects for all digitised images, the moment of inertia of the trunk segment and hence the radius of gyration ratio with respect to its mass centre ($k_c$) was calculated. A summary of the data have been provided in the results section, Table 5.7). The individual data are listed in the following table (Table 5.2b).
Table 5.2b. Moment of Inertia (I) of the trunk segments about its mass centre based on Zatsiorsky and Seluanov (1983) data combined with scaled digitised measurements using photographic images in A5.2a.

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<td>0.26085</td>
<td>0.47022</td>
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<tr>
<td>DDA331</td>
<td>67.95</td>
<td>2.66444</td>
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<td>DDA332</td>
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<td>2.64319</td>
<td>0.25400</td>
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<td>DDA333</td>
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<td>0.26497</td>
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<tr>
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<tr>
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<tr>
<td>CJP631</td>
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<tr>
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<td>StDev</td>
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Appendix 5.3. Root Mean Square Differences and Correlations between criterion trunk angles (Hip_HATcm) and approximated trunk angles (Hip_Shoulder and Hip_Ear).

<table>
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<th>Subject</th>
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<th>RMSD (°)</th>
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<td>Shld</td>
<td>Ear</td>
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<td>0.9673</td>
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<tr>
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<tr>
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<td>0.60</td>
<td>0.9980</td>
<td>0.9819</td>
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<tr>
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<td>3.10</td>
<td>0.9980</td>
<td>0.9819</td>
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<tr>
<td>SDev</td>
<td>0.84</td>
<td>0.60</td>
<td>0.9980</td>
<td>0.9819</td>
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<table>
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<td>Shld</td>
<td>Ear</td>
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<td>Shld</td>
<td>Ear</td>
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</table>

<table>
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<th>RMSD (°)</th>
<th>r</th>
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<td>Shld</td>
<td>Ear</td>
<td>Shld</td>
<td>Ear</td>
</tr>
<tr>
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<td>0.0201</td>
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</table>

Trial Identification (AAASJP)
where AAA = Subject's Initials, S = Subject number 1-8, J = Jump number 1-6 and P = jump Phase number 1-3
Data on the five filmed trails AAC14, DDA33, GCG431, AKS53 and CJP63
Marey = Combination of all three phases of the jump

RMSD Shld = Root Mean Square Difference between the trunk angles defined by the Hip to HATcm and the Hip to Shoulder links
RMSD Ear = Root Mean Square Difference between the trunk angles defined by the Hip to HATcm and the Hip to Ear links
r Shld = Pearson Product Moment correlation coefficient between the trunk angles defined by the Hip to HATcm and the Hip to Shoulder links
r Ear = Pearson Product Moment correlation coefficient between the trunk angles defined by the Hip to HATcm and the Hip to Ear links
Appendix 5.4. Neck Orientation angles plotted against percentage of Counter Movement Jump, Rebound Jump and Landing for 5 subjects.
263

Appendix 5.5 Integrated Marey Jump force plate data, 6 trials per subject for 8 subjects,
for two takeoffs and two landings including time duration, CM minimum and maximum
force
displacement,
at minimum squat and maximum velocity at takeoffs
vertical
vertical
and landings.
ID

N man

dtl

dt2

dU

d14 initial

minz2 minz3 maxzl maxz2 maxz3 max24

dzl

dz2

dz3

da4

hl

f22

W

vzl

va

va

TO

AAC 1 72.93 0264 0.208 0.224 2332 . 0.298 -0.152 0.08) 0.080 0.154 0.214 0.299 0378 0.306 0.366 0.299 1318 1733 693 2.509 -1.788 2363 "1.794
AAC 2 7273 0.264 0.208 0.224 0.176 -0224 -0.188 -0.077 0.139 0.103 0.153 0.117 0363 Q292 0.341 0.194 1396 1918 1069 2.216 .2322 2.276 "2.381
AAC

3 71.99 0.244 0.196 0.212 0.152 -0.230 -0.188 -0.093

0.115

S 72.82 0.240 0.204 0.236 0.148 -0213 -0.194 -0.074

0.145

OD81 0.133

0.093 0345 0.270 0.322 0.186 1433 1691 1220 2.438 "2.520 2.321 "2.440

AAC 4 72.45 0.256 0.212 0.224 0.216 . 0.167 -0.070 -0.067 0.207 0.197 0.262 0.167 0374 0.267 0.331 0.234 1425 1650 1064 2.457 . 231E 1163 -2.777
AAC

0.078

0.150

0.109 0.358 0.272 0.344 0.183 1464 1621 1453 2.316 .2.539 2.269 "2390

AAC 6 72.91 0.260 0.240 0.244 0.332 -0.131 41062 41129 0.231 0.230 0.284 0.172 0.362 0.292 0.346 0301 1328 1804 925 2.258 -2293 2.041 .2.549
RED 1 71.66
RED 2 71.29
RED 3 71.45
RED 4 71.21
RED 5 7136

0280
0288
0.268
0.284
0.288

0.416
0.424
0.400
0.288
0360

0.332
0.324
0.324
0.324
0.344

0.372
0.424
0.380
0.288
0320

-0326
-0351
-0319
-0342
-0351

-0.352
.0369
-0350
-0351

-0.272
-0329
-310

-0299
-0362 -0340

0.144
0.144
0.147
0.130
0.130

0.320
0.312
0.312
0.073
0.096

0.175 0.283 0.470 0.672 0327
0.156 0.321 0.495 0.681 0.526
0.165 0.295 0.466 0.662 0.515
0.167 0.105 0.472 0.423 M518
0.149 0.083 0.480 Q458 0.511

0.553
0.650
0.604
0.404
0.423

1745
1835
1806
1640
1711

1333
1533
0540
1511
1220

1250
1174
1342
1347
1271

2.582
2.561
2.648
2.671
2.626

-1.746
"1.747
"1.890
"1807
-2.689

2.604
2.588
2.539
2.642
2.567

"2.115
"1.799
-1.921
.2.796
-1750

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DDA

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0.095

3 67.94 0.184 0.268 0.236 0.172 -0.146 -0.176 . 0.068

0.126

0.111

S
6
1
2
3

-0.144 -0.189 -0.096
-0.142 -0.167 -0.066
-0.252 -0.209 -0.136
-0.246 -0.185 4159
-0.236 -0.214 -0.161

0.116 0.103
0.122 0.102
0.147 0.130
(1161 0.141
0.148 0130

-0.272 -0.198 -0.114
-0.236 -0.176 40.132
-0.292 -0.272 -0.105
-0.264 -0349 -0.279
-0.271 .0.285 -0.289

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0.146
0.158
0.159
0.175

0.140

0.112 0.249 0.277 0322 0.206 1816 1191 1286 1.981 4.045

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0.100 0.272 0.287 0312 0.168 1831 1.106 1240 2.0.19 . 2.084 1.887 -2.022

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DDA
DDA
GCG
GCG
GCG

68.06
67.97
76.11
75.70
75.87

0.176
0.176
0.236
0236
0.216

0.240
0228
0.264
0.364
0.248

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0.224
0.236
0.212
0.232

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0.172
0.192
0.204
0.228

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0.164
0.164
0.154

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0.339
0.326
0.344

0.331
0.321
0.373
0.349
0.368

0.211
0.188
0.267
0.300
Q288

1975
1884
1965
1999
2175

1352 1123
1372 1176
1699 1289
1611 1518
1.572 1240

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2.081
2.402
2.436
2.516

-2.049
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. 2.458
. 2..523

1.980
2.095
2370
2.409
2343

. 2.622
. 2.623
-2257
. 2.328
. 2.234

2.419
2.021
1.928
2.016
2.027

. 2.045
. 2.164
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. 2.447
. 2.386

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GCG
GCG
AKS
AKS
AKS

5 7533
675.90
1 59.74
2 59.75
3 59.74

0.236
0.216
0332
0.316
0324

0.248
0.164
0.336
0.344
0360

0.220
0.236
0.384
0.444
0.388

0.160
0.176
0.288
0.316
0332

0.143
0.113
(1116
(1093
0.132

0.149
0.281
Q178
0.166
0.180

0.129
0.132
0.128
0.112
0.117

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0.423
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0.387
0.442
0.417

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0.450
0.515
0.465

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0.264
0.234
0391
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2136
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1113
1142

1530
2626
IOQ3
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1020

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1538
732
986
898

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2.566
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2.089
2.095

-2.458
"2.384
"2.146
. 2.207
. 2263

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AKS

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0.129

0.087 0.153

0.104 0.443 0.424 0.490 0.419 1066

920

959 2.051 -2.161 2054 . 2198

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CJP
CJP
CJP
CJP
CJP
CJP
DJS

1
2
3
4
5
6
1

74.98
74.82
74.83
75.11
74.92
74.82
63.02

0.212
0.236
0.224
0.200
0.220
0.220
0.240

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0.216
0.280
0.224
0.248
0.208
0.228

0.288
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0.352
0.224
0.280
0.228
0.244

0220
0.208
0.244
0.192
0.212
0.256
0.168

0.136
0.131
0.113
0.124
0.161
-0.255 -0.268 -0.7-37 0.139
-0.234 -0.219 -0.097 0.150

-0.226
-0.285
-0.273
-0.220
-0.216

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41252 -0.170
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.0.281 41194

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(1105
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0.084
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0.097
0.097

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0.158

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0.094

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0.416
0385
0.345
0.397
0394
0.384

0.365
0.357
0.396
0.310
0.398
0.365
0.316

0.408
0.435
0.438
0.358
0.445
0.421
0.377

0.288
0.302
0.298
06260
0.291
0.346
0.190

1926
1911
1904
2109
2062
1999
1486

1315
1948
1176
1584
1755
2126
1655

1237
1352
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1540
1376
1289
1093

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2.284

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2.856
2.115

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3 64.35 0.232 0.288 0.240 0.132 -0.215 .0.197 -0.048

0.150

S 63.05 0.204 0.228 0.240 0.152 -0.210 -0.226 -0.100

0.133

MMK 1 67.19 0336 0.248 0.340 0.2L2 -0.261 -0.232 -0.170

0336

MMK3

67.04 0.248 0.316 0.344 0.220 -0.293 -0.228 -0.157

0.151

66.95 0.260 0348 0.260 0.316 -0.295 -0251 -0.175

0.169

DJS

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DJS 6 63.05 0.204 0.276 0.240 Q228 -0.211 -0.214 -0.163 0.129 0.178 0.132 0.091 0.341 0392 0.345 0.254 1591 1337 969 2.358 "2.064 2.242 "2335
0.164 0.357

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"2378

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0.342

0.366

0.193 0.444 0.570 0.594 0350

1904 1677 1547 2.661 . 1.792 1.541 "2365

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MMK5

0342

0.167

0345 0.464 0.593 0.418 0.520 1911 1594 1257 2.344 . 1.711 2.572 "1.722

MMK6 66.86 0.264 0352 0.280 0.280 -0303 -0.257 -0.184 0173 0.279 0.178 0314 0.476 0.536 0.435 0.498 1875 1281 1513 2.594 .2.088 2.603 "1.961
KEY
dt
minz
maxi
dz
12
v=

1-4: time intervals. stretch heights and takeoff velocities
1-3 : minimum displcmnentsand maximum forces at minimum squatpositions
am duration for ach of the 4 stagesof the Marey Jump
minimum displacementof CM relative to standing position= 0
maximum displacemat of CM relative to standing position - 0
difference between mine and maxi
vertical force at mmnnum squat position
vertical velocity at takeoff or landing


Appendix 5.6. Raw Force Data Signal Energy

5.6a. Summary of FFT analyses of Raw Vertical Ground Reaction Force data for the three phases of the Marey Jump showing frequencies below which 95%, 99% and 99.9% of the signal energy was contained for the 8 subjects over 6 trials per subject.

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th>RBJ</th>
<th>LDG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95.0%</td>
<td>99.0%</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>95.0%</td>
<td>99.0%</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>95.0%</td>
<td>99.0%</td>
<td>99.9%</td>
</tr>
<tr>
<td>AAC</td>
<td>2.44</td>
<td>3.26</td>
<td>6.10</td>
</tr>
<tr>
<td>RED</td>
<td>2.44</td>
<td>2.85</td>
<td>6.31</td>
</tr>
<tr>
<td>DDA</td>
<td>3.66</td>
<td>5.29</td>
<td>9.97</td>
</tr>
<tr>
<td>GCG</td>
<td>2.85</td>
<td>4.68</td>
<td>10.38</td>
</tr>
<tr>
<td>AKS</td>
<td>2.24</td>
<td>3.46</td>
<td>7.53</td>
</tr>
<tr>
<td>CJP</td>
<td>2.64</td>
<td>2.85</td>
<td>6.31</td>
</tr>
<tr>
<td>DJS</td>
<td>2.44</td>
<td>3.05</td>
<td>6.31</td>
</tr>
<tr>
<td>MMK</td>
<td>2.44</td>
<td>4.88</td>
<td>7.12</td>
</tr>
<tr>
<td>Mean</td>
<td>2.64</td>
<td>3.79</td>
<td>7.50</td>
</tr>
<tr>
<td>St.Dev</td>
<td>0.45</td>
<td>1.50</td>
<td>1.72</td>
</tr>
</tbody>
</table>

5.6b. ANOVA summary table of comparisons between jump phases and percentages of signal energy from FFT analysis of Marey Jumping actions for 8 subjects and 6 trials per subject, (Unfiltered Data @2.5 kHz).

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>df</th>
<th>Var</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump Phase</td>
<td>23587</td>
<td>2</td>
<td>11794</td>
<td>29.32(p&lt;0.01)</td>
</tr>
<tr>
<td>Percentages</td>
<td>17734</td>
<td>2</td>
<td>8867</td>
<td>51.71(p&lt;0.01)</td>
</tr>
<tr>
<td>Interaction</td>
<td>11953</td>
<td>4</td>
<td>2988</td>
<td>22.63(p&lt;0.01)</td>
</tr>
<tr>
<td>Jump x subject</td>
<td>5632</td>
<td>14</td>
<td>402</td>
<td></td>
</tr>
<tr>
<td>Percent x subject</td>
<td>2400</td>
<td>14</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>Interact x Subject</td>
<td>3697</td>
<td>28</td>
<td>132</td>
<td></td>
</tr>
</tbody>
</table>

The differences between the three phases of jumping were significant at the 1% level. Tukey tests revealed that only the differences between the rebound phase and the other two phases were significantly different and that the takeoff and landings were not different at the 1% level of significance.

5.6c. Tukey test analysis associated with the ANOVA summary in table 5.6b.

<table>
<thead>
<tr>
<th>Jumping Phase</th>
<th>Mean Differences</th>
<th>Percentage Signal Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(T&lt;sub&gt;0.05&lt;/sub&gt; = 12.30, T&lt;sub&gt;0.01&lt;/sub&gt; = 16.26)</td>
<td>(T&lt;sub&gt;0.05&lt;/sub&gt; = 8.45, T&lt;sub&gt;0.01&lt;/sub&gt; = 11.17)</td>
</tr>
<tr>
<td></td>
<td>RBJ</td>
<td>CMJ</td>
</tr>
<tr>
<td>RBJ</td>
<td>42.28**</td>
<td>9.59</td>
</tr>
<tr>
<td>CMJ</td>
<td>32.69**</td>
<td></td>
</tr>
</tbody>
</table>

(** = Significant at p<0.01)

CMJ = Counter Movement Jump, RBJ = Rebound Jump, LDG = Landing,
95%, 99% and 99.9% = All frequencies between DC and the Cutoff frequency, (fc = 256 Hz) required to accumulate 95%, 99% and 99.9% of the signal energy.
Appendix A5.7. Resultant Muscle Moment Data - A Comparison of Two Different Inertia Data Sets on Inverse Dynamics Analyses

Figure A5.7. Comparison of 'W' and 'Z' Inertia Data on the Determination of Resultant Muscle Moments using Inverse Dynamics Analyses.

Key: I = Impact, T = Takeoff, CMJ = Counter Movement Jump, RBJ = Rebound Jump, LDG = Landing, IDA = Inverse Dynamics Analysis, QSA = Quasi-Static Analysis, Z = Zatsiorsky Inertia Data, F = Butterworth Filter
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Appendix A5.8. Resultant Muscle Moment Data - A Comparison of Digital Filtering within Inverse Dynamics Analyses.

Figure A5.8. Comparison of a Butterworth Digital Filter on the Determination of Resultant Muscle Moments using Inverse Dynamics Analyses.

Key: I = Impact, T = Takeoff, CMJ = Counter Movement Jump, RBJ = Rebound Jump, LDG = Landing, IDA = Inverse Dynamics Analysis, QSA = Quasi-Statics Analysis, Z = Zatsiorsky Inertia Data, F = Butterworth Filter, R = Raw Data (i.e. no Butterworth Filtering)
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Appendix A5.9. Resultant Muscle Moment Data - A Comparison of Inverse Dynamics and Quasi-Statics Analysis Techniques

Figure A5.9. Comparison of Resultant Muscle Moments for Counter Movement Jump, Rebound Jump and Landing using Inverse Dynamics and Quasi-Statics Analyses. Key: I = Impact, T = Takeoff, CMJ = Counter Movement Jump, RBJ = Rebound Jump, LDG = Landing, IDA = Inverse Dynamics Analysis, QSA = Quasi-Statics Analysis, Z = Zatsiorsky Inertia Data, F = Butterworth Filter
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Appendix 5.10. Force Vector Plots of the rebound phase of the Marey Jump

Key: The white force plate image = time closest to the bottom of the squat, the bold open circle = mass centre, the light open circle = joint centre, the time is shown as time = 0 at impact. The vector arrow shows the magnitude, direction and point of force application at each instant in time for this 50Hz presentation of the rebound jump.
Appendix 5.11. Force Plate Data for subjects 1-8, showing mean of 6 trials ±1 Standard Deviation

Vertical Force ($F_z, N$) v Time (s)

**Key:** Takeoff is at time zero. Mean = solid line, dashed line = mean -1SD, dot dashed line = mean +1SD
Forces scaled to maximum trial data.
Appendix 5.11. Force Plate Data for subjects 1-8, showing mean of 6 trials ±1 Standard Deviation

Horizontal Force (Fy, N) v Time (s)

Key: Takeoff is at time zero. Mean = solid line, dashed line = mean-1SD, dot dashed line = mean =1SD
Forces scaled to maximum trial data.
Appendix 5.11. Force Plate Data for subjects 1-8, showing mean of 6 trials ±1 Standard Deviation
Horizontal Point of Force Application (ay, m) v Time (s)

Key: Takeoff is at time zero. Mean = solid line, dashed line = mean-1SD, dot dashed line = mean =1SD
Forces scaled to maximum trial data.
Appendix 5.12. Power Spectral Density Plots for Subjects 2-8

Key: The graphs on the left show the mean of 6 trials. The ones on the right present the data for the filmed trial.
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Appendix A5.13. Inverse Dynamics Analysis - A Comparison of 'W' and 'Z' Inertia Data In Moment, Power and Energy Analyses

Figure A5.13. Comparison of Relative Joint Angular Velocity, Resultant Muscle Moment, Muscle Moment Power and Energy for Ankle, Knee and Hip
Key: I = Impact, T = Takeoff, CMJ = Counter Movement Jump, RBJ = Rebound Jump, LDG = Landing, IDA = Inverse Dynamics Analysis, W = Winter Inertia Data, Z = Zatsiorsky Inertia Data, F = Butterworth Filter
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Appendix A5.13. Inverse Dynamics Analysis - A Comparison of 'W' and 'Z' Inertia Data In Moment, Power and Energy Analyses

Figure 5. : AnkleAKS,LDG IDA W data (B)
Figure 6. : AnkleAKS,LDG IDA Z data (B)
Figure 7. : KneeAKS,LDG IDA W data (B)
Figure 8. : KneeAKS,LDG IDA Z data (B)
Figure 9. : HipAKS,LDG IDA W data (B)
Figure 10. : HipAKS,LDG IDA Z data (B)

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The main programs for Chapter 3 were written in DAOS11 and Fortran IV to run on a PDP11/34+ mini computer. The hardware and software are no longer current and so the listings have not been included in this appendix. All the other programs have been modified and updated to run under Acorn RiscOS2.0 and RiscOS3.6 and have been included in the listings below.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Program</th>
</tr>
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<tbody>
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<td>B4.1</td>
<td>MareyJP</td>
</tr>
<tr>
<td>B5.1</td>
<td>!Cinedig</td>
</tr>
<tr>
<td>B5.1a</td>
<td>Cinefilm Digitising Reference Setupfile MareyRef</td>
</tr>
<tr>
<td>B5.1b</td>
<td>Cinefilm Digitising MaryJump Setupfile MarJmp1</td>
</tr>
<tr>
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<td>!Convert</td>
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<td>Rmsdx9</td>
</tr>
<tr>
<td>B5.4</td>
<td>dswor9</td>
</tr>
<tr>
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<td>Marey</td>
</tr>
<tr>
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<td>MareyPSD</td>
</tr>
<tr>
<td>B5.7</td>
<td>FFTnrgM</td>
</tr>
<tr>
<td>B5.8</td>
<td>MeanPWR</td>
</tr>
<tr>
<td>B5.9</td>
<td>ZatWinCM (including angle determination)</td>
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<tr>
<td>B5.10</td>
<td>MomentsA (With automatic determination of cutoff frequency)</td>
</tr>
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<td>DrawVector</td>
</tr>
<tr>
<td>B5.12</td>
<td>DrawMM</td>
</tr>
<tr>
<td>B5.13</td>
<td>DrawPWR</td>
</tr>
<tr>
<td>B5.14</td>
<td>LIBRARY of Commands Common to all CED1401 Programmes</td>
</tr>
<tr>
<td>B5.15</td>
<td>CEDcsv (Data transfer routine within I/O library)</td>
</tr>
</tbody>
</table>

A series of file conversion programs were written to enable data in one format to be converted to another, e.g. comma separated format for transfer into spreadsheet applications. A sample of one of these routines has been listed as B5.15, but the the main library !RunImage is required to enable this series of functions and procedures to run. The !RunImage Library published in the Acorn User Magazine, IDG Publishing, February 1993, was written by D. Acton and D. Lawrence. In addition the CED library of Commands was produced by Cambridge Electronic Design Limited, Science Park, Milton Road, Cambridge, CB4 4FE.

All the other software in the following listings was written by D.G.Kerwin.

The programs listings are available as document Volume II by request from The Department of Physical Education, Sports Science and Recreation Management, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK.