Energy and Pole Ground Reaction Force
Contributions to Pole Vault Performance

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ABSTRACT

Effective performance in the pole vault event is heavily reliant on the efficient transfer of energy throughout the vaulting phase. The overall principle of this energy transfer is not complex with the approach used to generate the initial kinetic energy. This is transferred into elastic potential energy (EPE), stored in the pole. This EPE is converted into gravitational potential energy (GPE) of the vaulter as the pole bends and then recoils. Research into the pole vault has generally separated the pole and the vaulter with more recent studies beginning to investigate vaulter energy. Pole ground reaction forces (GRF) have had limited examination despite their potential to be incorporated as an influential analysis tool. There is a lack of published data characterising poles, how they bend and their specific storage capabilities. The energy calculations have previously used representative body parameters that are not specific to the population being investigated. Coupled with this then is a limited understanding of the effect on the final energy calculations. The present thesis addresses these limitations with an overall aim of determining performance in pole vaulting. The investigations are presented as chapters. Three studies are included which examine the vaults of eight elite level male and female pole vaulters and the individual poles used. A further chapter is included that utilised a case study approach to investigate two different vaults, with substantially different performance outcomes, from one of the elite female vaulters.

Study one investigated the specific poles for characterisation beyond their manufacturer ratings using dynamic and quasi-static bending methods. The development of a custom designed pole bending system was the initial part of this study. A bilinear fitting method was employed providing four variables to distinguish between poles. A more advanced empirical function was developed to calculate the curve based partially on previous literature. The results indicated that poles behave differently between bending regimes with greater energy stored and lost for slow dynamic bending compared with quasi-static. This investigation showed that it is possible to model the pole’s response and then provide integration up to any point for calculation of energy that could be incorporated in the following studies for determining performance.

Study two indicated that incorporating different body segment parameters can have significant impact on final energy calculations when conducting experiments on specific populations. Results indicate that wherever possible individual specific body segment parameters should be incorporated to provide greater relevance to the target population.
Furthermore, males presented higher energy results at specific time points throughout the vault when using subject specific body segment data. Comparisons of waveform data provided little significant differences between males and females, only GPE displayed any difference. The total vaulter energy at maximum pole bend and the overall total vaulter energy were found to affect the performance of a vault.

Study three demonstrated that pole GRF can be developed as an effective tool for pole vault biomechanical analysis. However, for effective technique prescription in applied settings it may be beneficial to provide individual specific analyses as grouping of participants for complicated elite sporting events may mask potential findings. No significant differences were found between males and females for mass normalised force. Variables that were expected to correlate with peak height did not eventuate. The similarities in the force profiles between genders and differing performance outcomes suggest that eventual performance may not be distinguishable from the pole GRF profiles alone as there are other factors in the vaulting manouvre that are likely accounting for any changes to the outcome of the vault.

This thesis demonstrates the importance of providing a complete analysis the pole vault event and minimising assumptions made to both the pole and the vaulter when determining performance. A more detailed method of characterising and modelling a pole’s bend was presented and incorporated into vault analysis. Additionally, body specific energy calculations were found to impact the final energy through the vault. Furthermore, although GRF data can provide an additional tool for biomechanical feedback it does not provide the ability to distinguish performance. Ultimately these finding add to the limited information that exists regarding performance in pole vaulting.
TABLE OF CONTENTS

Abstract ............................................................................................................................. 1
Table of Contents .............................................................................................................. 3
List of Figures ................................................................................................................... 8
List of Tables ................................................................................................................... 13
List of Abbreviations ....................................................................................................... 16
Acknowledgements ......................................................................................................... 17
Declaration ....................................................................................................................... 19

Chapter One
Background to the Problem

1.1 Introduction ............................................................................................................... 21
1.2 Statement of the Problem .......................................................................................... 24
1.3 Aims and Hypotheses .............................................................................................. 24
   1.3.1 Study One ..................................................................................................... 24
   1.3.2 Study Two ..................................................................................................... 25
   1.3.3 Study Three ................................................................................................... 26
   1.3.4 Case Study .................................................................................................... 27
1.4 Significance of the Investigation ............................................................................... 27
1.5 Delimitations and Limitations ................................................................................... 29

Chapter Two
Literature Review

2.1 Introduction to the Pole Vault Event ......................................................................... 31
   2.1.1 The Vaulter ................................................................................................... 32
   2.1.2 The Pole Vault ‘Pole’ .................................................................................... 32
2.1.3 Rules and Regulations .......................................................................................... 33
2.1.4 Phase Breakdown.................................................................................................. 34
2.2 Energy in the Pole Vault .......................................................................................... 35
  2.2.1 Energy of the Phases ...................................................................................... 36
  2.2.2 Energy and the Pole ...................................................................................... 41
2.3 Pole Vault Kinematics ............................................................................................. 46
  2.3.1 Field Based Motion Analysis ........................................................................ 46
  2.3.2 Two-Dimensional vs Three-Dimensional Analysis ..................................... 46
  2.3.3 Direct and Indirect Calculation of Segment Parameters ............................... 48
2.4 Pole Vault Kinetics ................................................................................................ 50
2.5 Summary ............................................................................................................. 51

Chapter Three

Extended Methods

3.1 Instrumented Pole Plant Box ................................................................................ 54
3.2 Three Dimensional Load Cell Calibration .......................................................... 54
  3.2.1 Static Calibration .......................................................................................... 56
  2.3.2 Dynamic Calibration ..................................................................................... 60
3.3 Pole Bending System Development ..................................................................... 61
3.4 Body Segmentation Procedures .......................................................................... 64
3.5 Pole Vault Data Collection ................................................................................... 68

Chapter Four

The Dynamics of the Vaulting Pole

4.1 Introduction .......................................................................................................... 75
4.2 Methods ............................................................................................................ 77
Chapter Five

The effect of body segment inertial parameter methodologies on energy calculations in male and female pole vaulters and energetic parameters as performance indicators

5.1 Introduction .................................................................................................................. 97

5.2 Methods ....................................................................................................................... 99

5.2.1 Participants ............................................................................................................. 99

5.2.2 Procedures ............................................................................................................. 99

5.2.3 Data Treatment ...................................................................................................... 100

5.3 Results and Discussion .............................................................................................. 102

5.3.1 Body segment inertial parameters ....................................................................... 102

5.3.2 Effect of varying segment models on energy calculations ................................. 104

5.3.3 Energy in the pole vault ....................................................................................... 111

5.3.4 Discrete energy variables correlated to peak height ......................................... 117

5.4 Summary and Conclusions ...................................................................................... 118
5.4.1 Review of Hypotheses ................................................................. 118
5.4.2 Conclusions .............................................................................. 119

Chapter Six

Ground reaction forces for male and female pole vaulters and determination of performance indicators

6.1 Introduction .................................................................................. 122
6.2 Methods .......................................................................................... 123
   6.2.1 Participants ............................................................................. 123
   6.2.2 Procedures ............................................................................ 123
   6.2.4 Data Treatment .................................................................... 124
6.3 Results and Discussion ................................................................. 125
   6.3.1 Ground Reaction Force Data Overview ............................... 125
   6.3.2 Discrete Comparisons of Male and Female Pole Vaulters ....... 127
   6.3.3 Comparison of Force Curves ................................................. 129
   6.3.4 Predictors of Peak Height .................................................... 132
6.4 Summary and Conclusions .......................................................... 133
   6.4.1 Review of Hypotheses ......................................................... 133
   6.4.2 Conclusions ...................................................................... 133

Chapter Seven

Putting it all together: A case study of elite female pole vaulting

7.1 A Case Study of an Elite Female Pole Vaulter .............................. 136

Chapter Eight

8.1 Summary ..................................................................................... 148
LIST OF FIGURES

Figure 2.1: Example photo sequence of a female pole vaulter (Alana Boyd) from Australian Nationals competition, 2009 .......................................................... 31

Figure 2.2: Pole plant box dimensions (IAAF Track and Field Facilities Manual, 2008) ............................................................................................................................... 34

Figure 3.1: Diagram of the instrumented pole plant box installation .................. 55

Figure 3.2: (a) Front section of pole plant box on the load cell; (b) pole plant box in-situ .............................................................................................................................. 55

Figure 3.3: The load cell with the base and top plate attached; metal plate attachment for weight support ........................................................................................................... 57

Figure 3.4: The calibration mount bolted to wall girder; set up for anterior-posterior (X) and lateral (Y) calibration ............................................................................................... 57

Figure 3.5: Vertical (Z) calibration weight adding sequence, 20kg weights up to 100kg .......................................................................................................................... 58

Figure 3.6: Static calibration of the load cell in the anterior-posterior (X), lateral (Y) and vertical (Z) direction .................................................................................................. 59

Figure 3.7: Load cell dynamic response characterisation ........................................ 60
Figure 3.8: Transverse (birds-eye) view of the pole bending system during load-deformation testing................................................................. 61

Figure 3.9: Initial designs diagrams for the pole bending system ......................... 62

Figure 3.10: (a) Electric winch and mounting for the load cell; (b) trolley with hollow sleeve for pole end ................................................................. 63

Figure 3.11: (a) The DXA scanner; (b) The Artec L™ 3D scanner ....................... 64

Figure 3.12: Example of a 3D whole body scan................................................. 65

Figure 3.13: The BMD, Tissue and Total mass images from the DXA scan .......... 66

Figure 3.14: Segmenting of DXA image in Matlab.............................................. 67

Figure 3.15: Representation of the camera positions for pole vault data collection..... 70

Figure 3.16: Screenshots from all 6 camera views .............................................. 71

Figure 3.17: Example placement of the calibration cube................................. 71

Figure 4.1: Above view of the pole bending system during load-deformation testing.. 77

Figure 4.2: Testing setup for replication of pole flex measurement ..................... 78
**Figure 4.3:** Example quasi-static data; lines of best fit to the low and high regions for both loading and unloading, corner point shown on the loading data ............................... 83

**Figure 4.4:** Example force vs displacement for quasi-static bending trial fitting for loading and unloading using Equation 9................................................................. 85

**Figure 4.5:** Example force vs displacement for quasi-static (above) and slow dynamic (below) trial for the same pole ..................................................................................... 86

**Figure 4.6:** Comparison of bilinear slopes for all poles for loading and unloading using both quasi-static and dynamic bending methods. The red line depicts a slope of 1 (equality between the two methods) and the black is a line of best fit to the data. Standard deviation are also shown for each pole ............................................................. 88

**Figure 5.1:** Mean mass-normalised rotational KE and total vaulter energy for the DXA and Chandler BSIP methodologies for the male pole vaulters (N=4). Shaded areas indicate ±1 standard deviation. To the right are the statistical parametric maps, areas outside the dotted limits denote significance with p values inset. All curves are normalised over the vault phase initial energy to peak height ................................................. 110

**Figure 5.2:** Mean and standard deviation of total energy, kinetic energy, gravitational potential energy and elastic potential energy for men (n=4) and women (n=4). Values are normalised to body mass. The x-axis is normalised to have -100% at the initial point, 0% at maximum pole bend and 100% at the instant of peak centre of mass height............................................................................................................................ 112
**Figure 5.3:** Comparison of the total energy of the vaulter at discrete time points in the vault: Initial, Maximum Pole Bend, Pole Straight, and Peak Height as well as the calculated energy decrease, increase and total energy gained ............................... 114

**Figure 5.4:** Mass normalised male and female average and SD for energy calculations (translational KE, rotational KE, GPE, total vaulter energy and total overall energy) in the vaulting phase time normalised from initial to PH. SPM results displaying significant (p<0.05) differences on the left. 50% represents the temporal point MPB ................................. 115-116

**Figure 6.1:** Representative graph of the typical force profile for Anterior-Posterior (forceX), Lateral (forceY), Vertical (forceZ) components and the resultant pole GRF (force_mag) .................................................................................................................................. 125

**Figure 6.2:** Representative graph of typical force profile with phase breakdown; Phase A (pole plant to the peak in anterior-posterior force), Phase B (peak anterior-posterior force to MPB), Phase C (MPB to peak in vertical force) and Phase D (peak in vertical force to force end) .................................................................................................................................. 127

**Figure 6.3:** SPM comparisons of average anterior-posterior (X), lateral (Y), vertical (Z) and resultant total pole GRF (ForceTotal) for males and females ................................. 130

**Figure 7.1:** Mass normalised total vaulter energy (a), gravitational potential energy (b), translational kinetic energy (c) and rotational kinetic energy (d) for vaulting phase from initial to peak height. One female vaulter’s best and worst performing vaults. 50% is the point of maximum pole bend for both the energy and kinetic curves ................................. 139
**Figure 7.2**: Total force, X (anterior-posterior) force and Z (vertical) force from mid final stride flight phase to peak height. The vertical line encompasses the MPB for both vaults with the force profiles synchronised to pole plant. The lateral (Y) force profile was not presented as it displayed minimal force........................................................... 140

**Figure 7.3**: Sagittal plane sequence from approximated maximum pole bend to peak COM height at temporal points 0.58s; 0.82s; 1.0s; 1.22s and 1.54s from pole plant ... 142

**Figure 7.3**: Posterior view sequence from approximated maximum pole bend to peak COM height at temporal points 0.58s; 0.82s; 1.0s; 1.22s and 1.54s from pole plant .......................................................... 143
LIST OF TABLES

Table 3.1: Participant details............................................................................................................... 71

Table 4.1: Characteristics of tested poles; length (m), weight rating (lb/kg), manufacturer flex rating (cm), measured flex and measured pre-bend. Poles 15 and 16 are poles 11 and 3 respectively, reduced to the grip length used in the dynamic trials. Poles 1 and 4 were measured experimental poles excluded as they were not used in this analysis........................................................................................................................................... 81

Table 4.2: R-squared values for a linear fit to load-deformation curves on all poles.... 82

Table 4.3: Corner point force (newtons) and displacement (x in cm) for the Loading and Unloading of each pole for both quasi-static (QS) and dynamic bending Methods........................................................................................................................................ 89

Table 4.4: The maximum force applied, calculated energy stored, returned, lost and the percentage energy loss for all poles using the quasi-static bending method........... 91

Table 4.5: The maximum force applied, calculated energy stored, returned, lost and the percentage energy loss for all poles using the dynamic bending method............. 92

Table 5.1: Mean (SD) segment percentage of body mass for male (4) and female (4) pole vaulters using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model......................................................... 105
Table 5.2: Mean (SD) percentage of the segment length for segment centre of mass position from proximal end point for male (4) and female (4) pole vaulters using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model……………………………………………………………………..106

Table 5.3: Mean (SD) coefficient of variation of rotational kinetic energy and total vaulter energy for males (4) and females (4) calculated across all vaults using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model………………………………………………………………………107

Table 5.4: Percentage differences for segment mass between the Indirect BSIP methods and the DXA. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model………………………………………………………………………………….108

Table 5.5: Percentage differences for segment COM location between the Indirect BSIP methods and the DXA. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model………………………………………………………………………………….108

Table 6.1: Average and SD for normalised force of all male (1-4) and female (5-8) pole vaulters……………………………………………………………………………………….128
Table 6.2: Phase time and total time for males and females………………………..128

Table 6.2: Phase and total impulse for males and females…………………………128

Table 7.1: Discrete variables from two vaults performed by the same vaulter…….138
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>APAS</td>
<td>Ariel Performance Analysis System</td>
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<td>BSIP</td>
<td>Body Segment Inertial Parameters</td>
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<td>C</td>
<td>Modified Chandler method</td>
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<tr>
<td>COM</td>
<td>Centre Of Mass</td>
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<tr>
<td>CT</td>
<td>Computed Tomography</td>
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<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
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<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>DXA</td>
<td>Dual-energy X-ray Absorptiometry</td>
</tr>
<tr>
<td>EPE</td>
<td>Elastic Potential Energy (Also strain energy)</td>
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<tr>
<td>GPE</td>
<td>Gravitational Potential Energy</td>
</tr>
<tr>
<td>GRF</td>
<td>Ground Reaction Force</td>
</tr>
<tr>
<td>IAAF</td>
<td>International Association of Athletics Federations</td>
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<tr>
<td>KE</td>
<td>Kinetic Energy</td>
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<tr>
<td>LED</td>
<td>Light emitting diode</td>
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<tr>
<td>MPB</td>
<td>Maximum Pole Bend</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>PH</td>
<td>Peak Height</td>
</tr>
<tr>
<td>PP</td>
<td>The instant of pole plant</td>
</tr>
<tr>
<td>PS</td>
<td>The instant of Pole Straight</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SPM</td>
<td>Statistical Parametric Mapping</td>
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<tr>
<td>UWA</td>
<td>University if Western Australia</td>
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<tr>
<td>WAIS</td>
<td>Western Australian Institute of Sport</td>
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<tr>
<td>Y</td>
<td>Modified Yeadon method</td>
</tr>
<tr>
<td>Z1</td>
<td>Zatsiorsky Simple Regression method</td>
</tr>
<tr>
<td>Z2</td>
<td>Zatsiorsky Multiple Regression</td>
</tr>
<tr>
<td>Z3</td>
<td>Zatsiorsky Geometric Model</td>
</tr>
</tbody>
</table>
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DECLARATION

I declare this thesis is my own composition, all sources have been acknowledged and my contribution is clearly identified in the thesis.

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Introduction
1.1 INTRODUCTION
The fundamental objective of the pole vault event is to jump as high as possible and successfully clear the bar. It is not only one of the most exciting and fascinating events in athletics but also one of the most technical (Linthorne, 2000; Young, 2002). The pole vaulter uses a flexible pole to assist them to jump over a horizontal bar positioned 4-6 m from the ground. The vault is a complex interaction of speed, strength, power and technique, involving many elements that make it one of the most technically complicated and acrobatic of the field events. Through incorporating high levels of sprinting, jumping and gymnastic ability, the vaulter uses the flexible pole to transfer energy from their running approach through the vaulting manoeuvre. Effective performance is heavily reliant on efficient energy transfer through each of the vaulting phases. Initially present in the form of kinetic energy (KE), that is transferred into elastic potential energy (EPE) in the compressed pole, and lastly gravitational potential energy (GPE) of the vaulter as the pole recoils. Critical to this energy transfer is the storage and recovery phase of EPE in the poles which transitions the initial phase KE to final phase GPE.

Similar to many technical demanding sporting tasks, the vault is sequential in nature where any small technique alteration may have a marked effect on outcome performance. Each phase of the vault is a natural consequence of the previous phase, such that latter phases can be difficult or impossible to perform, if the preceding technique is inefficient or incorrect (Greig & Yeadon, 1995; Young, 2002; Gardner, 1990). Consequently the approach and take-off of the vaulter are crucial, with the conversion of KE (produced from the approach) to GPE being of primary importance (Linthorne, 2000; Tidow, 1989). Advancements at the elite level in pole vault focus heavily on the identification of technique inefficiencies and the causative factors for optimal performance. However there is a paucity of research with this aim and subsequently, limited investigations aimed at describing the complex interaction dynamics of the vaulter-pole system.

Pole vaulting sports biomechanics research has traditionally examined the pole and the vaulter in isolation. The pole vault is a unique athletic event as performance reliant on an implement or tool to facilitate the displacement of the athlete via additional energy input; and as such the pole’s construction and its performance dynamics are vital (Jahromi, 2012). A stronger, lighter and more flexible pole has had an extraordinary
effect on heights achieved (Ekevad & Lundberg, 1997). This is evidenced by the change from a rigid to a flexible pole in the early 1960’s; where developments in materials technology served to increase the men’s world record from 4.80m to today’s mark of 6.16m. The length and stiffness of the poles vary, and with the selection of these characteristics largely determined by individual vaulter preference, pole characteristics are clearly an extremely important component of overall performance success (Jahromi et al., 2012). The EPE in the pole is the combined result of the compressive force and the bending moment that the athlete applies to the pole. However, previous research approaches have not incorporated pole specific mechanical characteristics; specifically strain energy used to derive how the energy is stored and its recoil, into EPE equations. Though yet to be undertaken, Linthorne (2000) previously suggested that the categorisation of poles by their ability to store and recoil energy is warranted in future pole vaulting research.

Due to the field location requirements of the vault and the safety limitations (no markers affixed to the athlete) previous technique analyses have generally employed a two-dimensional (2D) approach. The adoption of the more widely accepted gold-standard three-dimensional (3D) analysis may provide for improved accuracy in derived kinematic and kinetic outputs of the vault. More specifically, 3D analysis will serve to aid in the development of an energy-orientated analysis approach, a growing research direction for investigations examining the pole vault event. In previous research, this direction has been typically limited to analysis of the absolute energy values at discrete phases of the vault (Arampatzis et al., 2004; Schade et al., 2000; Schade et al., 2004; Schade et al., 2007), as opposed to any cohesive understanding of the energy flow into and out of the pole (continuous data), as it relates to the resultant full body centre of mass (COM) height reached by the vaulter. An accurate and non-invasive method of calculating subject specific segment masses and location of segment COM, coupled with a clear understanding of the continual total energy flow changes from the pole to the vaulter would likely improve the accuracy of the calculated energy data and enable easier and more relevant identification of technique inefficiencies.

Body segment inertial parameters (BSIP) are essential for analysing human motion and include segment mass and the COM location information. BSIPs are required when the biomechanist wishes to use Newton-Euler equations to derive force, moment of force and power (work) information. The most commonly encountered method biomechanists
use to source BSIP information is via indirect estimation methods which generally involve regression equations developed from empirical data (average sample information) collected from human cadaver specimens (Chandler et al., 1975; Dempster, 1955; Yeadon, 1990) or from imaging techniques. Indirect measurement of BSIPs is widely and preferentially used in mechanical analysis as it involves the direct reading of existing anthropometric BSIP information tables. However, a major limitation using this approach is that the original empirical data used in the development of the regression equation may not be representative of the target population being investigated (Durkin & Dowling, 2003). The direct approach involves calculating subject specific BSIP directly from the participant via imaging techniques such as such as dual-energy X-ray absorptiometry (DXA). Direct methods are therefore more accurate and robust than standard regression tables and certainly more relevant for populations found book-ending the average normative scale (e.g. elite athletes).

Describing the interaction between the pole and the vaulter is essential to understanding the force profiles of the vault. A crucial area in pole vault that has not been examined is the 3D forces that are applied to the pole plant box at the base of the pole. Pole ground reaction forces (GRF) have been previously investigated (Morlier & Mesnard, 2007) however no attempt was made to associate resultant pole GRF profiles and overall performance. Given that pole GRFs provide an indication of the kinetic strategies employed by the vaulter, any attempt to identify causal relationships between pole GRF profiles and optimal vaulting performance is warranted.

This research will examine both male and female elite pole vaulters in an attempt to improve the applied understanding surrounding factors influencing pole vaulting success across genders. A selection of commercially manufactured poles used by the vaulters will first be characterised according to their mechanical properties (bending behaviour). Total energy flow through the vault will be comprehensively examined and related to pole vault performance, taking into account the 3D motion of the body and the individual pole characteristics. Additionally, the effect of implementing subject-specific direct BSIP methods compared with multiple indirect methods on the total energy calculations will be explored. The 3D pole GRF will be examined in an attempt to identify technique factors associated with jump height performance. Finally a case study of a female pole vault will be discussed to apply the findings of the three experimental studies to a specific comparison of two vaults from one of the athletes.
1.2 STATEMENT OF THE PROBLEM

The methods used by manufacturers for determining characteristics of poles do not provide a detailed account pole bending behaviour. Furthermore, the energy storage, loss and return characteristics of individual poles have not been previously reported. Energy components facilitating vaulter performance has been previously reported in a limited capacity, however substantial simplifications and assumptions were made in the research, particularly with respect to pole energy and BSIP contributions. The analysis of pole GRF is a relatively new direction for the sport, with limited research assessing reaction force profiles and their applicability as a rapid feedback tool for performance assessment. Further research examining factors that may lead to a better understanding of the primary energy contributions to the vault, incorporating pole and the vaulter interaction, is clearly warranted.

1.3 AIMS AND HYPOTHESES

1.3.1 The Dynamics of the Vaulting Pole

This study focuses on the dynamics of the pole and its contribution to the pole vault, how it absorbs and recoils energy. It is necessary to characterise a pole’s bend and elastic properties, taking into account any non-uniformity. Poles will have different generalised manufacturer ratings which are given as their weight and flex ratings; therefore a number of poles were tested to observe their behaviour beyond these ratings and to also determine their bending characteristics. The outcome of this is to more thoroughly characterise the elastic properties of individual poles and provide pole specific methods that can be incorporated into pole vaulting analysis. This will allow more specific performance-based results to be determined and the optimisation of technique to achieve greater vault heights.

This study was aimed primarily as a characterisation study to;

i. Develop effective pole testing methods that would be more relevant to the behaviour of the pole within the vaulting manoeuvre.

ii. Characterise the elastic properties of poles with a more complex method than the manufacturer rating methodology via analysis of pole behaviour using two bending regimes; quasi-static and dynamic bending.

iii. Determine the pole’s energy contribution and develop modelling methodologies that can allow this information to be incorporated into a vault analysis.
It was hypothesised that;

i. Poles will have a non-uniform bend when determining their deformation under different loads.

ii. Higher pole energy storage capabilities will be displayed during slow speed dynamic bending when compared with quasi-static measures.

iii. The percentage of energy lost through the pole in bending will be higher during slow dynamic compared with quasi-static bending regimes.

1.3.2 Energetic measures as performance indicators: Do body specific inertial parameters effect energy calculations in male and female pole vaulters.

BSIP information is required for mechanical analysis (e.g. inverse dynamics) and several direct and indirect methods for estimating these parameters have been established. However, the effect BSIP variation (error) on derived energy calculations is currently unknown in vaulting analysis.

This study provides a description of the vaulting technique through investigation of the energy components that contribute to the pole vaulting action and specifically investigates whether these energy characteristics can be related to the achieved overall vault height (performance). The body’s total energy as well as its GPE, translational and rotational KE were calculated in conjunction with the pole specific stored EPE in the pole, which has not previously been included in the total energy description. Discrete energy data was compared along with SPM analysis between male and female pole vaulters.

The aims of this study were to;

i. To investigate the variation of the direct subject specific BSIP estimation method (DXA) against five indirect methods in an elite pole vaulting athlete sample.

ii. To determine if variation in the direct and indirect BSIP methodologies affect the calculation of the rotational KE and total energy in the pole vault.

iii. Utilise direct BSIP to assess differences between male and female vaulters.

iv. Determine if energetic variables are correlated to the peak height of the COM.

It was hypothesised that;
i. There will be significant difference between segment mass and COM location determined using the DXA method compared with the five indirect estimation methods.

ii. There will be significant difference in the total vaulter energy and rotational KE calculated with the DXA method compared with the five indirect methodologies.

iii. When calculating mass normalised energy parameters using only the DXA method:
   a. Males will exhibit greater total vaulter energy compared with females at each of the time points of the vault; initial, maximum pole bend, pole straight and peak height, as well as for calculated values of energy changes between phases; energy decrease, increase and gain.
   b. From a comparison of waveform data for the energy components of the vaulter (translational KE, rotational KE, GPE and total), and the overall total energy (incorporating EPE) will be significantly greater in male vaulters compared with females.
   c. Initial KE and overall energy will be positively correlated with peak height.

1.3.3 Are pole ground reaction forces indicative of performance in elite pole vaulters?

This study provides a description of the vaulting strategies applied through investigation of the 3D pole GRF characteristics. The pole GRF will be analysed at discrete points through the entire vault and also as a continuous profile over time. A comparison of mass-normalised force profile curves between males and females for each component of the force is presented using statistical parametric mapping analysis (SPM) (Pataky, Robinson and Vanrenterghem, 2013). Variables from the pole GRF during vaulting have not previously been researched. The force in the direction of pole bend has been previously reported in the calculation of pole energy, however the 3D force profile was not investigated for variables that may be significant to vault heights achieved. Kinetic variables examined in this study were calculated from the 3D GRF, the anterior-posterior (X), lateral (Y), and vertical (Z) directions. The timing of the peak forces and maximum pole bend were also examined. These variables were chosen from previous analyses and pilot studies as theoretical and practical representations of kinetic variables influencing pole vault performance. Using peak COM height as the criterion variable, a
regression analysis was performed to determine those kinetic variables best predict peak COM height.

The aims of this study were to;

i. Investigate kinetic profile parameters for male and female pole vaulters.
ii. Provide comparisons of mass-normalised force curves between male and female pole vaulters.
iii. Identify the pole GRF measures that best predict peak COM height.

The hypotheses were;

i. Male vaulters will display increased normalised force and impulse at discrete phase points; peak anterior-posterior force, maximum pole bend and peak vertical force, when compared with female vaulters.
ii. There will be no significant difference between males and females in the absolute timing of discrete time points in the force profile; peak anterior-posterior, maximum pole bend and peak vertical.
iii. Mass normalised anterior-posterior, lateral, vertical and resultant values will be higher in males compared with females across the entire vault (waveform SPM analysis).
iv. Maximum vertical force and overall total impulse will be positively correlated with peak height in all vaulters.

1.3.4 Putting it all together: A case study of an elite female pole vaulter

This final chapter applies the findings from the previous three experimental studies in a comparison of two vaults with substantially different performance outcomes from one of the elite female vaulters in the study. The aims of this study were to postulate potential causative factors associated with the resultant height differences between the two vaults, based on findings derived in the previous chapters.

1.4 SIGNIFICANCE OF THE INVESTIGATION

The initial portion of this research is devoted to understanding the dynamics of the poles with the aim of developing a thorough and detailed method for calculating the stored pole energy. The manufacturer ratings for each pole do not provide coaches and vaulters with a full classification of the pole. How a pole stores and recoils the energy in the vault is relatively unknown and this research provides further analysis of the pole
characteristics to facilitate enhanced understanding of pole dynamics. From a practical perspective, the ability to provide quick and meaningful feedback on performance factors to athletes and coaches is essential. The energy storage in the pole is an aspect of pole vaulting that has not previously been provided as the feedback paradigm due to a lack of understanding of pole bending characteristics.

The second study examines the energy calculations in the pole vault and how manipulating the methods of calculating BSIP may affect the calculation of energy throughout the vault. No previous research has investigated the effect of using subject specific BSIP in targeted athlete populations with reference to derived total energy calculations. Producing an individual vaulter-specific energy flow, determining energetic strategies employed by vaulters and incorporating pole load-deformation characteristics provides the coaches and athletes with previously unattainable information.

The third and final study comprises an investigation of the 3D pole ground reaction forces and how these can be interpreted to determine influential variables to success. Pole ground reaction forces have been shown in previous studies although these measures have not been used as a method of evaluating vaulting strategies.

This research project has a direct benefit in improving the performance and consistency of targeted elite vaulters, ensuring continual success at the international level. Previous research has provided little insight in the area of energy contribution from the pole. Energy flow throughout the pole vault has been discussed generally or in terms of discrete data points, whereas this study provides a greater understanding of energy flow through the entire vaulting phase with the inclusion of the specific pole EPE information. This investigation implements ground reaction force analysis, which is a relatively new direction in the sport as a potential method of determining vaulter strategies.

The outcomes of this research will provide a comprehensive analysis of the pole and athlete kinetic contributions to the vaulting manoeuvre, with the overall aim of facilitating enhanced technique prescription modifications in the sport of pole vaulting.
1.5 LIMITATIONS AND DELIMITATIONS

1.5.1 Limitations
   i. All athletes were participating on a voluntary basis. Therefore, motivation levels may have an impact on performance during the testing sessions.
   ii. All trials were conducted during training sessions in as close to ideal conditions as possible. The testing was performed in an indoor location and it is assumed that minor variations in environmental conditions such as temperature and humidity had minimal effect on results.

1.5.2 Delimitations
   i. The findings of these studies are restricted to the sample used in each of the three studies. Although the entire elite pole vaulting sample available in Australia participated in the research, the small number of participants with unequal jump numbers decreases the generalisability of the results.
   ii. All athletes were highly trained, and recruited from a squad of pole vault athletes (Western Australia Institute of Sport) and targeted athletes from other Australian Sports Institutes as well international elite athletes.
Literature Review
2.1 INTRODUCTION TO THE POLE VAULT EVENT

Pole-vault is an event in which male and female athletes use a flexible pole to assist them to jump over a horizontal bar. Competition consists of a sequential increase in bar height with the athlete’s allowed a maximum of three consecutive misses before they are eliminated from the competition. The final height successfully jumped by each athlete is then used to determine the final order of the competition. Pole vaulting is a technically demanding athletic field event (Schade, Arampatzis, & Brueggemann, 2004) that has a high degree of skill difficulty. The vaulter must develop a high velocity during their approach run whilst carrying the flexible pole of ~4-5 metres long. This pole is then guided into the back the pole plant-box, which is built into the ground and is designed to provide the pivot point for the base of the pole. As the base of the pole is in the plant-box the pole begins to bend and the vaulter takes off from the ground. The bend in the pole combined with the subsequent vaulter actions catapult the athlete’s centre of mass (COM) upwards to clear the bar (Railsback, 1987). An example photo sequence is shown in Figure 2.1.

![Figure 2.1. Example photo sequence of a female pole vaulter (Alana Boyd) from Australian Nationals competition, 2009.](image-url)
2.1.1 The Vaulter

The pole vault requires technically complicated acrobatics (Tidow, 1989), and incorporates high levels of sprinting, jumping and gymnastic ability. Successful pole vaulting requires a fast run-up, enough strength to create and withstand high stresses, excellent coordination and the technical ability to perform the vault. Maximum approach velocities in elite competition have been recorded above 9m.s\(^{-1}\) (Tidow, 1989). It is a complex skill to place the pole in the optimal position at the back of the plant-box. The vaulter must be capable of controlling the pole during a fast approach until it is accurately lowered in the final strides.

When the pole contacts the back of the plant box, the vaulter must be strong enough to brace against the impact and apply sufficient force to create the pole bend. As the pole compresses and bends, and then recoils into a straight position, vaulters can add work to the vaulter-pole system through applied force on the pole, provided their techniques are sufficiently skilful.

There are differences between male and female pole vaulters; however, elite level coaches generally believe their technical models are becoming more similar (Personal Communication – Alex Parnov, WAIS Pole Vault Coach). The major differences occur due to the approach velocity, strength/power ability and therefore, poles size and stiffness (Schade, Arampatzis, Bruggemann, & Komi, 2004).

2.1.2 The Pole Vault ‘Pole’

Using a tool (the pole) to improve performance makes the pole vault a unique event; the use of a pole allows athletes to clear greater heights than without it. This is evidenced by the world record for the pole vault of 6.16m for males and 5.06m for females being higher than for the high jump event (2.45m for males and 2.09 for females) where no pole is used. However, using a pole to achieve a higher jump also increases the technicality of the event, because the interactions of vaulter and pole influence performances (Schade & Arampatzis, 2012). As the pole propels the vaulter to achieve the desired outcome, its construction, dynamics and performance is important.

The world record height for the pole vault has regularly progressed over time, there is some evidence that modern vaulting poles have contributed to these progressions. Wood, iron and bamboo were the first materials used for the pole. From the early 20th century, bamboo was well suited to vaulting due to its hollow structure and toughness;
and was used to achieve world records until the 1950’s. Aluminium tube poles were then used and improved the world records until being replaced by fibreglass, carbon fibre and composites of these materials. Flexible poles replaced the original more rigid types in the early 1960’s, and developments in materials and technology were reported to have contributed to increases in the men’s world record increasing from 4.80m to its current level (Burgess, 1998).

The pole vault is different from other sports because the pole is more individualised as it needs to be tailored specifically to each vaulter. The vaulter’s body morphology, sprinting capabilities, muscular strength, acrobatic skill, and well synchronised sequencing of the different phases, all can influence the pole best suited to the individual vaulter. Vaulters usually carry a number of poles to competitions and training. Each pole is constructed to a specific length and diameter, the desired stiffness and weight ratings specified by the vaulter for different scenarios. Vaulters change the poles that they use according to how well they are jumping, environmental conditions and how high the bar is set. As the bar gets higher, a vaulter may increase their grip height on the pole, even change the pole length and/or select a pole with increased stiffness. Based on training session experiences, a vaulter learns when these pole set-ups need to be adopted. Increasing the grip height or pole stiffness makes it possible for a vaulter to increase the vault peak height, if all other technical factors are unchanged. Deriving optimal technique models for pole vaulting is challenging due to its technical nature without access to detailed biomechanical information (Ekevad & Lundberg, 1995; Linthorne, 2000).

2.1.3 Rules and Regulations

The rules for the pole vault event allow a vaulter to manipulate the bar positioning as well as the poles that they use. The bar can be moved in the direction of the landing area from the zero point (directly above the back end of the plant box) to any distance up to 80cm towards the landing area. The plant box and its dimensions must adhere to specific specifications as shown in Figure 2.2.
A vaulter cannot move their top grip hand higher up the pole during a vault or place their lower hand above the higher on the pole. To increase the ability of the vaulter to grip the pole they are permitted to use a substance on their hands.

The International Association of Athletics Federations (IAAF) rules governing the construction and regulations of poles are relatively uncomplicated and have few restrictions. The pole can be made of any material, or combination of materials, and be of any length or diameter; but the basic surface must be smooth (IAAF, 2011). The IAAF rules allow layers of tape or material on the pole for both hand grip and pole protection. However, the materials must not create a sudden change in diameter of the pole. Poles must consist of a single structure (consistent material) and have no pre-stored energy (Burgess, 1998). Nonetheless, these restrictions still provide plenty of scope for variation in the poles used by vaulters around the world, in both materials and geometry.

2.1.4 Phase Breakdown

Research into pole vaulting is usually divided into approach, take-off, support and flight phases (G. C. Bogdanis & Yeadon, 1994; Hubbard, 1980).

(a) During the **approach**, the aim is to achieve a high horizontal velocity to maximise energy for the take-off. This begins at the start of the run-up of ~30-45m long, and requires elite vaulters to be very competent sprinters (Hubbard, 1980). The athlete typically aims to reach maximum velocity in the final steps
before take-off. Typically, the vaulter velocity levels off due to a level of visual targeting to attain the optimal take-off position at pole plant.

(b) Transferring the horizontal energy achieved in the run-up, into the pole is critical in plant and take-off. Optimal take-off angles of ~16-20 degrees to horizontal at high velocity [8-10 m.s\(^{-1}\)] have been suggested for a successful performance (Linthorne, 2000; Linthorne & Gemma Weetman, 2012). The pole plant is the process of the athlete accurately placing the base of the pole into the plant box (Angulo-Kinzler et al., 1994; G. C. Bogdanis & Yeadon, 1994; Hubbard, 1980; Petrov, 2004), this action must be fast but controlled, with the arms reaching up as high as possible to prevent excessive horizontal braking forces at plant (Adamczewski & Perlt, 1997).

(c) The support phase is characterised by the rotation of the pole in the plant-box, and the athlete about the pole. This begins when the athlete leaves the ground, and ends with the push-off or release of the pole (Angulo-Kinzler et al., 1994; G. Bogdanis & Yeadon, 1993; Greig & Yeadon, 1995; Mueller & Hommel, 1997; Railsback, 1987; M. A. Young, 2002). The vaulter’s body position greatly influences the efficiency of this phase. This is related to the body position partially determining how much energy is transferred to, and stored in, the pole; and then how much is returned to the jump. With greater vertical velocity of the athlete at the end of this phase, a higher jump will result. This phase can also be divided into two parts by the point of maximum pole bend (MPB); this creates pole loading and pole unloading sub-phases.

(d) The flight phase is the free flight of the vaulter over the bar (or not if unsuccessful) and requires sufficient vertical and horizontal velocities, as well as body manoeuvres to assist clearance.

2.2 ENERGY IN THE POLE VAULT

Effectiveness in pole vault is heavily reliant on the efficient transfer of energy throughout the vaulting phase. The overall principle of this energy transfer is not complex. The runway approach is used to generate the initial kinetic energy (KE). This is transferred into elastic potential energy (EPE), also termed strain energy, stored in the pole when the pole is positioned into the pole plant box and the momentum of the vaulter acts to bend the pole. This EPE is converted into gravitational potential energy (GPE) of the vaulter as the pole bends and then recoils returning the energy stored to the vaulter. The effective production, storage and application of these energies are
necessary for success. Velocity in the run-up enables the vaulter to create the initial energy for the vault. The basic reason for using a pole in the pole vault event is to convert the KE of the vaulter developed during the run-up into GPE in the vaulter to clear the bar (Burgess, 1998). The more efficient these sequential transformations, the more energy can be regained from the pole in later phases.

2.2.1 Energy of the Phases

The timing of the vault sub-sectional sequences with high levels of force and velocity, are critical because any small variation in technique or force application can markedly affect performance. Because each phase of the vault is highly influenced by the previous phase, smooth transitions from the earlier sub-sections into the later phases are essential. It can be difficult to regain the movement patterns if the transitioning is sequentially compromised (Falk, 1993; Gardner, 1990; McGinnis, 1997; Railsback, 1987; Zagorac, Retelj, & Katic, 2008). The approach and take-off phases have been recognised as potentially the biggest determining factors in pole vault performance (Adamczewski & Perlt, 1997). Thus, the run-up and take-off are critical in producing large amounts of KE (produced in the approach), which can then be efficiently transferred to GPE to maximise the subsequent phases of the vault (Linthorne, 2000; Tidow, 1989).

Previous energy studies have investigated a breakdown of the energy phases within the pole vault through calculating the athletes total body energy (Arampatzis, Schade, & Brüggemann, 2004; Schade, Arampatzis, & Brüggemann, 2000, 2006; Schade et al., 2004). To track the energy through the vault, the vaulting sequence can be broken down using specific points, at which the energies can be calculated, with the point of MPB separating the phases (Arampatzis et al., 2004). Important energy parameters calculated in the first part leading up to MPB include; the initial energy of the athlete, the energy of the athlete and the pole at the point of MPB, the work of the athlete up until MPB and the energy of the total system at MPB. After the MPB through to the point of maximum height is the second part of the interaction between the vaulter and the pole (Arampatzis et al., 2004; Schade et al., 2006); the energy components calculated in this phase included the final energy of the athlete, the energy added by the athlete during the phase, the energy loss in the pole and the total energy gained by the athlete from the initial energy.
Arampatzis et al. (2004) and Schade et al. (2006) conducted analysis on five males and one female while Schade et al. (2004) conducted analysis on 10 males and 10 females both using 3D video analysis with four cameras. These cameras were set up with two focussing on the initial phase and the others on the later phase based on methods discussed by Schade et al. (2000). Biomechanical analysis of elite sporting populations can be challenging especially with an individual sport such as pole vaulting due to available populations that are often small. Comparisons of five males to one female can show differences for that population however will be difficult to infer over larger populations when only one athlete is in the female group. The comparison from the 2000 Sydney Olympics (Schade et al. 2004) have a greater population of both males and females however only one jump attempt was analysed for each vaulter which may not be a true representation of each participant and could affect the statistical power of the results.

The approach Phase is where the maximum initial KE is obtained. Superficially, it may be concluded that having a higher peak horizontal velocity close to take-off will lead to improved jump performances. Theoretically, the peak height a pole-vaulter can reach is highly related to the run-up velocity. This is because the greater the horizontal velocity, the more energy is available to be transferred into the take-off (Adamczewski & Perlt, 1997; Linthorne, 2000; McGinnis, 1997; Schade et al., 2000; Sloan, 1993; Sutcliffe, 1989; Tidow, 1989; Young & Yeadon, 1997). When observing approach velocities globally, over different ages, experience levels and gender, a higher velocity approach is associated with an increase in vault height (Adamczewski & Perlt, 1997). However, when analysing within-performance populations, the peak horizontal approach velocity does not differentiate between vaulters (Mueller & Hommel, 1997). A vaulter with a slightly lower velocity may record a greater peak height due to a more effective pole plant; using a different technique or pole and/or an ability to input more energy into the vault.

When deliberately manipulating approach velocities, such as by altering the run-up length, where a decreased run-up length provides a significantly decreased velocity, vaulters may display net energy changes and resultant height differences (Linthorne & Weetman, 2012). This will only develop when changes in velocities are large; and, the effect decreases as the velocities increase and are more similar. However, despite this, a faster approach velocity has a large impact on pole vault heights achieved. Variations to
an athlete’s approach velocity can also cause changes in technique, including minor systematic changes in kinematics. These changes could also be attributed to the different poles used as the velocity of the approach increased (Linthorne & Weetman, 2012).

The **plant and take-off phase** relies on the transition of the horizontal energy produced from the velocity in the approach. Until an athlete has sufficient strength and technical ability to withstand the forces developed in the process of pole plant and take-off with increased velocity, any benefit of the increased initial KE may be compromised (Graham-Smith & Lees, 2005; Linthorne, 2000). The balance between velocity, strength and technique must be combined for a successful pole vault. Coaches and researchers often regard the take-off as the most important aspect of the vault, as this is where the major energy transfers begin to take place (Falk, 1993; Gardner, 1990; Schade et al., 2000; Young & Yeadon, 1997).

As well as developing a high horizontal velocity, a controlled approach is necessary for accurate stride positions and pole-plant, resulting in a more optimal take-off position. During the plant and take-off placing the base of the pole into the plant-box accurately is essential. The requirement for accuracy is assisted by the velocity levelling off, or slightly decreasing during the last strides of the approach. This decrease in velocity will result in decreased initial KE at the take-off and therefore must be minimised. This small velocity decrease is also important for enabling the vaulter to increase their vertical take-off angle.

Previous research has reported that a greater take-off angle is important and that the optimum angle is around 15-20° (Gardner, 1990; Linthorne, 2000; Sutcliffe, 1989). Based on the inter-relationship between the horizontal and vertical velocities in human jumping, any increase in the COM take-off angle usually corresponds to the decrease in horizontal velocity, which causes a decrease in the initial horizontal KE. Research into the long jump take-off concludes that in order to increase the vertical velocity at take-off, there must be a concomitant decrease in the horizontal velocity (Graham-Smith & Lees, 2005). While the pole vault take-off is not exactly the same as for long jump the same principal applies.

The take-off velocity is more important than take-off angle for the long jump because the distance lost due to a lower velocity approach was greater than that of take-off angle changes (Linthorne, Guzman, & Bridgett, 2005). With the necessity for maximum
initial energy in the pole vault this importance of greater take-off velocity is also relevant. Pole-vaulters strive for optimum take-off angles in order to minimise the amount of energy lost during the transition from horizontal to vertical velocities. However, a critical balance is required between any decrease in horizontal velocity and achieving the greatest vertical velocity for the steepest take-off angle possible. If this is not achieved an increased proportion of energy developed in the approach will be lost through take-off and not transferred into the pole.

A major area of energy loss at plant is when the tip of the pole changes from moving at \(-8-10\text{ m.s}^{-1}\) to a complete stop in an instant as it makes contact with the back of the plant box. These energy losses are dissipated into the plant-box (Linthorne, 2000), pole and through the vaulters body. Minimising losses in the plant maximises the initial KE transferred into the vault. Little can be done by the athlete about the impact losses at the base of the pole due to vibration, sound and heat. The vaulter’s body will absorb a portion of the impact force created when the pole hits the back of the plant-box throughout the musculo-skeletal system. Controlling the losses at the top end of the pole is necessary to transfer maximum energy into the pole.

During the support phase the pole vaulter must convert the velocity of the COM from horizontal to vertical, using the interaction of the pole with the ground through the pole-plant and swing (period from the plant to maximum pole bend). It is here that large energy transformations take place (Adamczewski & Perlt, 1997; Angulo-Kinzler et al., 1994; Armbrust, 1993; Falk, 1993; Frère, L'Hermette, Slawinski, & Tourny-Chollet, 2010; Gardner, 1990; Hubbard, 1980; Linthorne, 2000; McGinnis, 1997; Sutcliffe, 1989; Young & Yeadon, 1997). While the majority of energy in the pole vault is produced from the run-up, more energy can be added during the support phase by the vaulter applying work to the pole. This is the process of actively manipulating the pole while being suspended; a vaulter can apply a bending moment through the application of forces about the upper and lower hand grip as they swing through the support phase. This application of a bending moment may assist to bend the pole in the first part of the swing phase and then also allow the vaulter to gain more energy back from the pole as it straightens (Fukushima, Nishikawa, Tanaka, & Kuniyoshi, 2013; Griner, 1984). While it is beneficial to study the different phases in vaulting manoeuvres, it is necessary to examine the vault as a whole.
Previous research has developed an energy-oriented approach for analysing pole vault (Arampatzis et al., 2004; Schade, Arampatzis, & Brueggemann, 2004; Schade et al., 2000, 2006; Schade & Brueggemann, 2006). However, thus far, studies have sought to reproduce and analyse energy at discrete phases of the vault, rather than the energy flow into, and out of, the vaulter’s pole. Maximising the production and minimising the loss of energy through the vault is important, and has a large impact on technique and success (Arampatzis et al., 2004; Linthorne, 2000; Linthorne & Weetman, 2012). To maximise KE, the vaulter must build up to near maximum velocity by the end of the run-up. The KE is a result of the velocity and the mass of the vaulter. This can be calculated

Equation (1) for a vaulter with mass \( m \) plus pole mass \( m_p \) at velocity \( v \):

\[
KE_1 = \frac{1}{2} (m + m_p)v^2
\]

The EPE in the pole is produced from take-off, when the pole begins to bend, through to maximum pole bend (MPB). A greater bend in the pole equates to higher EPE in that pole. As the energy of the run-up is transferred into the pole, the pole bends due to the momentum of the vaulter, and the initial KE of the vaulter begins to be transferred into GPE (Linthorne, 2000). A higher initial KE means that, potentially, a greater amount of EPE can be stored in the pole. As the vaulter swings on the pole and exerts a bending moment via the hand grip, he/she is maximising the energy transfer into the pole. This is achieved by the vaulter’s mass rotating about the pivot point (upper hand position) in the initial pole loading sub-phase. Also, the stiffness and length of the pole are determining factors for the amount of EPE that can be stored in the pole (Ekevad & Lundberg, 1997).

The GPE is developed as a result of actions at the take-off. However, high levels of GPE are only reached after MPB when the pole recoils to catapult the vaulter into the air. Here the initial KE is regained by the vaulter vertically as GPE which is then the major energy component after MPB, and reaches its maximum value when the vaulter’s COM reaches peak height. Experienced vaulters can actively produce work on the pole during the second half of the support phase, as the pole begins to extend, in an effort to increase the vertical lift and push-off (Arampatzis et al., 2004; Schade et al., 2004).

The total energy at any stage in the vault can be calculated by taking into account all the energies at that time, including the energy loss. This has previously been calculated
using the vaulter’s mass \((m)\), velocity \((v)\) and height of the COM \((h)\) shown in equation 2 (Schade et al., 2000); where \(I\) is the moment of inertia, \(\omega\) is the angular velocity of each segment \((ith)\) about its transversal axis \((iTr)\) and the trunk about its longitudinal axis \((TLo)\).

\[
E_{tot} = \sum_{i=1}^{12} m_i g h n_i + \sum_{i=1}^{12} \frac{m_i v_i^2}{2} + \sum_{i=1}^{12} \frac{l_{iTr} \omega_{iTr}^2}{2} + \frac{l_{TLo} \omega_{TLo}^2}{2} \tag{2}
\]

Energy flow impacts on the performance of the pole vault, and the degree of skilled ‘technique’ influences this flow. Ideally, there will be a smooth energy flow through the vault, with efficient transitions between the major energy contributions. The more efficient this transformation of energy into the pole, the more energy can be recovered from the pole in later phases for any given pole. Subsequently, while it has been reported that initial velocity is important in the creation of initial KE, how this KE is transferred into EPE and GPE requires further investigation (Arampatzis et al., 2004; Linthorne & Weetman, 2012).

The flight phase is the period after pole release and is defined by the release of the pole and the free flight of the vaulter. At this stage, most of the vaulter’s motion is vertical to gain height. However, some horizontal velocity is required for the body to pass over the bar. The relationship of pole choice and levels of expertise, anatomical strengths, acrobatic skill and other technique variations are valuable to ensure successful clearance of the bar (Arampatzis et al., 2004; Linthorne, 2000). For example, too little horizontal velocity may achieve a greater height but the vaulter may not have enough forward motion and could land on the bar, and therefore the result is unsuccessful. In contrast, excessive horizontal velocity prevents maximising the height and the vaulter could go through, instead of over, the bar.

### 2.2.2 Energy and the Pole

Three main functions for the pole during a vault have been identified; energy storage, a pivoting column and a stiffness function (Burgess, 1998). Energy storage occurs via the large deflections/bending in the pole that results from the transferring initial energy created during the run-up, when the pole connects with the end of the pole plant-box. As the pole is deforming, it stores energy until MPB is reached. A proportion of that energy will be regained from the pole when it recoils in the later phases of the vault. In concert with the pole bend, the base of the pole also pivots around its contact point with the plant box to allow the flow of the vaulter from a primarily horizontal velocity to a more
vertical trajectory. This has been described as a double pendulum action during the 
vaulting phase, whereby the pole rotates forward about the pole plant box; while the 
vaulter rotates about the end of the pole (Katsikas, Papaiakovou, Pilianidis, & Kollias, 
2003). Although this description may be simplistic in describing the vaulting 
mechanics, it does highlight the importance of the timing required within this event.

The double pendulum better explains the body rotations about the top of the pole, and 
the base of the pole in the plant-box. The synchronisation of movement sequences are 
important for maintaining momentum, enabling completion of the vault and 
maximising efficient transfer of forces throughout the vault (Katsikas et al., 2003). The 
stiffness function of the pole needs consideration due to bending and torsion loads the 
vaulter applies to the pole, and which are not only in the x-y plane (Burgess, 1998). This 
is directly related to the energy storage function, with the pole stiffness determining part 
of the energy storage.

As well as only a few regulations regarding pole construction, there is little published 
research into how the poles bend. Pole studies generally have been based around 
modelling the pole bend using general stiffness functions and optimisation through 
these models. Jahromi et al. (2012) conducted an optimization of poles to determine the 
effect of pole length and stiffness using a genetic algorithm. This investigation provided 
proof of the importance of the pole length and stiffness in effective pole vaulting and 
identified margins for these parameters. How different pole vault poles behave during a 
vault, or even on their own when placed under load remains unclear.

Active bending of the pole is recognised as essential by coaches and athletes, and has 
been modelled to present a method for pole use (Fukushima et al., 2013). Euler buckling 
models were used to analyse pole vaulting by treating the force exerted by the pole as a 
simple constant force. A more accurate representation would include variable support at 
the top end of the pole to represent the influence of the bending moment.

Fukushima et al. (2013) adopted a transitional buckling model to improve the model 
performance and to represent the active bending effect on the pole. Conclusions from 
this investigation showed that the input of a bending moment and the timing of the 
change of bending moment direction to improved vaulting performance. This model 
was developed for a robotic tool to perform the manoeuvre and, while it provides a 
guide to how the vaulter can apply a moment to the pole, it is yet to be implemented.
The ability to store EPE and manage the effective return of this energy in the performance is central to efficient pole vaulting. Greater understanding of pole deformation is needed, and the storage and recoil of the pole energy during a vault needs further investigation.

Currently, poles are constructed by using a cylindrical shell, or mandrel, for a skeleton; with a sail piece (sheet of fibreglass/carbon fibre material) wrapped around it until reaching the desired stiffness and weight rating. This is achieved by successively altering the wall thickness along the pole when winding on the sail piece. This wall thickness change, due to the number of layers of the sail piece, will alter the bending characteristics of the pole; including changing where along the pole will the greatest amount of bend occur. Also, during this process, poles are often given a pre-bend to induce bending at the beginning of the vault and ensure that the pole bends in the desired direction (Burgess, 1998).

Poles range around 4-5 meters in length and the vaulters chosen lengths, diameters and weight ratings can remain relatively fixed, but they do change the flex ratings frequently. The weight rating is determined by the mass of the vaulter and is generally a safety rating that serves as a guide to the physical limit of the pole bend/loading, after which it may fracture. However, the flex rating is the main variable that vaulters change when switching between poles, and is provided by the manufacturer for approximating the stiffness of the pole. One method of developing the flex number employed by some manufacturers (e.g. Spirit Fibreglass Poles) is to measure of the bending deflection of the centre of the pole when it is supported horizontally at both ends and has a 50lb (22.7kg) mass suspended from the middle. The amount of change in the position of the pole centre when the mass is added is given as the flex rating in centimetres. With a stiffer pole this amount of change will be decreased and therefore the flex rating decreases. For example a pole that has a flex rating of 20.0 will be stiffer than a pole with flex 21.0 of the same length.

A vaulter will begin their training session or competition with a softer pole (higher flex rating) and as they increase their jump height they will generally transition onto poles with lower flex ratings; this transition is not standardised as all vaulters will use different poles and vary in their ability and strength; therefore this is a product of experience and practice. While this flex rating measurement does distinguish between poles, it does not provide a direct comparison between poles of different manufacturers,
material composition or have any relevance to how the pole bends under a compressive force as which occurs during a vault where the manufacturer obtains the measurement is taken in one dimension with the load applied at the centre of the pole. Therefore, it is necessary to characterise the poles used with reference to the energy that it can store during a vault.

Stronger, lighter and more flexible poles have had a major influence on heights achieved since their introduction by the World Athletic Federation in 1961 (Ekevad & Lundberg, 1997; Zagorac et al., 2008). The pole-vaulter aims to put as much energy from the approach into the pole as possible. This is achieved during the plant and subsequent work done on the pole prior to maximum pole bend - a process commonly referred to as ‘penetration’ (Tidow, 1989; Young & Yeandon, 1997). This ‘penetration’ begins at the pole plant and continues until MPB, when the initial energy has been transferred to the pole. Penetration can be influenced by body positions assumed after take-off (Tidow, 1989) and the horizontal velocity of the athlete’s mass.

The EPE in the pole, $E_{pole}$, is the combined result of the compressive force into the plant-box and the bending moment the vaulter applies on the pole. It has been calculated by using the ground reaction forces at the base of the pole, and by the kinematics of the pole bend (Schade et al., 2004), via the following equation:

$$E_{pole} = \int F_p \cdot dr + \int M \cdot d\beta$$

(3)

Where $F_p$ is the resolved force in the direction of pole deformation, $r$ is the pole chord length, $M$ is the bending moment to the upper end of the pole and $\beta$ is the angle between the top pole tangent (line between the top and bottom hand grip positions on the pole) and the pole chord.

Equation 3 does not account for the bending characteristics of the pole itself. The pole deformation depends upon the forces applied and the common parameters used to describe the elastic deformation of materials. These common parameters that have been used in modelling the pole bend have included the Young’s modulus ($Y$), Shear modulus ($G$), linear (Hooke’s law) vs. non-linear (polynomial) model, and the moment of inertia ($I$) (Lee & Kuo, 1993). The Young’s modulus essentially is determined by the materials used to manufacture the pole, usually fibreglass or carbon fibre. The shear modulus also is related to the materials used and the cross-sectional geometry of the pole. Hooke’s law (4) for a linear spring gives the force ($F$) as:
\[ F = -ks \]  \hspace{1cm} (4)

And the elastic energy \((U)\) stored is the integral of the force:

\[ U = \int_0^s ksds = \frac{1}{2} ks^2 \]  \hspace{1cm} (5)

Where \(k\) is the spring constant and \(s\) is the chord length (Fowles, 1986). Equations 4 and 5 follow the assumption that the pole will act as a simple linear spring but this is unlikely. Hence, higher order terms may occur, especially with large deflections, and the polynomial expansion is perhaps better reflected by:

\[ F = -\sum_i k_is^i = -k_1s - k_2s^2 - k_3s^3 \ldots \]  \hspace{1cm} (6)

\[ U = \int_0^s ksds = \sum_i \int_0^s k_is^idS = \frac{1}{2} k_1s^2 + \frac{1}{3} k_2s^3 + \frac{1}{4} k_3s^4 + \ldots \]  \hspace{1cm} (7)

The presence of higher order terms \((k_2, k_3 \ldots)\) will modify the interpretation of stored elastic potential energy vs chord length. By static measurements of \(|F|\) vs. \(|s|\), the elastic energy dependence on \(|s|\) can be fully characterised. The moment of inertia depends on the mass of the pole \((m_p)\), its length \((L)\), the pole’s cross sectional geometry and the position of the rotation axis of the vaulter relative to the pole.

With a flexible and longer pole, pole-vaulters can reduce energy loss due to the impact of take-off than when using a rigid pole (Linthorne, 2000). Therefore, take-off velocity is greater and more of the initial energy can be transferred into the pole. The position of the body through the vault also can add to the energy transferred. Prior to MPB, a vaulter tries to exert as much force on the pole as possible so as to bend it more. Then, as the pole recoils, the pole-vaulter should be positioned for the energy from the pole to be transferred into vertical motion.

Previous studies of pole movement characteristics have assumed uniform bending (Ekevad & Lundberg, 1997; Linthorne, 2000). However, it is accepted that the poles are non-uniform and most are manufactured with a ‘pre-bend’ (Linthorne, 2000). Therefore, the uniform bending issue needs further investigation. A pole’s local bending rigidities have been analysed by experimental and modelling procedures to investigate the effect of non-uniform poles (Morlier, Mesnard, & Cid, 2008). Forces were applied to two different poles to investigate their energy storage and the evolution of poles with better technology. There were significant differences found between the two poles, with these differences attributed to the design evolution in pole manufacturing. This investigation
provided evidence of non-uniform bending in poles and also differences between poles due to their manufacturing process. While the protocol used to conduct the experimental procedures on the poles provide an improvement to pole characterisation, these results were not related back to an actual vault performance.

The importance of the pole can be noted through the athlete’s total energy exceeding the total energy at take-off (Fukushima et al., 2013). Investigation of the mechanics of the pole, in terms of its EPE; how it is stored and recoiled, have not previously been attempted for a specific pole used in a pole vault. As previously mentioned, there are differences between poles which may change how energy is stored, and the amount of energy which can be stored and retrieved. This is an area where there has been limited research; therefore, the consequence of pole mechanics needs further investigation.

2.3 POLE VAULT KINEMATICS

2.3.1 Field Based Motion Analysis

An accurate and non-invasive method for calculating a vaulter’s COM, coupled with an in-depth understanding of the continual energy flow changes throughout the complex event phases, would improve the validity of results and allow easier identification of the athlete’s strengths and weaknesses. Laboratory versus field testing is a regular challenge in biomechanical analyses of sporting events. More detailed analyses are required which, ideally, should be conducted during competition or carefully simulated environments (Elliott & Alderson, 2007). Laboratory motion analysis systems and related software developments are now available which can study complex movements with increasingly greater accuracy. However, this is often at the expense of the validity benefits that come with field testing. Currently, the marker-based opto-reflective systems are regarded as the gold standard in biomechanical motion analysis, but video based systems have been used in field settings for deriving kinematics. The more complex and expensive opto-reflective systems tend to be laboratory based. The latter are more invasive on the participant, and do not lend themselves well to analyses during competitive performances.

2.3.2 Two-Dimensional (2D) vs Three-Dimensional (3D) Analysis

A 2D approach for analysis is a more accessible option for field testing. A case study of one participant used a 2D approach to examine the run-up velocities in the pole vault with performance, kinematics and energy exchanges (Linthorne & Weetman, 2012).
This was a 2D case study of one participant after digitising 18 body landmarks. One limitation of 2D is the inability to determine any out-of-plane motion which is coupled with variances between trials where there are any lateral deviations away from the calibrated plane.

Comparing 2D and 3D methods when calculating energy in the pole vault, (Schade et al., 2000) found that the difference between the calculated energy parameters supports using 2D for COM because movements lateral to the direction of travel are negligible. However for the plane calibration issue indicated previously and the potential for different individual techniques to display greater out of plane movements, the use of 2D analysis for comparative purposes is not ideal. The justification for the use of 2D calculations does also come at the expense of accuracy for more in-depth comparisons of full body segments, rather than just the COM (Schade et al., 2000). In this comparative methodological accuracy study for determining variances in energy calculations, the z-coordinate from the 3D digitising was set to zero to produce the 2D energy calculations, which therefore neglects any movement in the third dimension. In practicality, this is different to how 2D motion analysis data is typically derived, as a 3D volume is used for calibration. Results from the study indicate that 2D analysis for deriving energy values is adequate for primary parameters at discrete points in the vault (initial energy; energy at MPB; final energy). However, differences will vary throughout the jump and, while this method may provide a less labour intensive analysis, wherever possible 3D analysis should be encouraged. The vaulter’s energy values has also been found to depend on the accuracy of manual video digitising methods used to derive the energy values, which can limit the accuracy of the overall results (Schade et al., 2000). While 3D analysis using two cameras has been shown to be effective there are increased errors from digitising especially when the movement is complex and involves out of plane motion. Multiple camera set up for 3D analysis should be employed wherever possible to decrease the inherent errors that come with manual digitising.

This comparison of 2D and 3D has also been conducted in kinematic analysis of running where differences have been found between energy calculations due to the movements in the z-axis (Metzler, Arampatzis, & Brueggemann, 2002). When the body was broken down to analyse individual segments, these differences are exaggerated and become more significant between the 2D and 3D analyses (Metzler et al., 2002).
Therefore in an event such as the pole vault, where there are movements in all three planes, 3D analyses should be conducted whenever possible.

Three-dimensional analyses for the pole vault have attempted to gather more accurate insight into the relevant technique. Many of the mechanical studies in pole vaulting have been simulation based as with the modelling of poles. A more complete analysis of a vaulter in 3D is necessary for further understanding of the main phases in the vault. Optimising the athletic movements and specific characteristics of effective vaulting technique, and then producing understandable presentation of this information (Morlier & Cid, 1996) is yet to be achieved.

2.3.3 Direct and Indirect Calculation of Segment Parameters

Body segment inertial parameters (BSIP) are essential for analysing human motion. These parameters include segment mass, COM and the principle moments of inertia; and can be calculated either indirectly or directly. Indirect measures are based on empirical data from previous investigations on cadavers and are estimated using specific anthropometric values. The direct approach for calculating BSIP can include subject specific measures such as medical imaging technologies including magnetic resonance imaging (MRI), computed tomography (CT) and dual-energy X-ray absorptiometry (DXA) or derived directly from cadavers.

Indirect measurement of BSIP is widely adopted as it is simpler, more accessible, anthropometric data values can be measured quickly, equipment and facilities are inexpensive, and there is no radiation risk. These indirect methods calculate the BSIP from anthropometric values using regression equations (Chandler, Clauser, McConville, Reynolds, & Young, 1975; de Leva, 1996; Dempster, 1955; Durkin & Dowling, 2003; Zatsiorsky & Seluyanov, 1983) or geometric models (Durkin & Dowling, 2006; Zatsiorsky, Seluyanov, & Chugunova, 1990) that are derived from cadaveric data. Although the indirect data collection procedures have many advantages, there are large errors created when applied to physically different populations from which the cadaver measures were derived. Body morphologies of elite athletes may be optimized specifically for the sport in which they participate (Olds and Tomkinson, 2009) leading to differences in BSIP compared with general population. Therefore, these equations should be interpreted with caution when they are not representative of the population under investigation (Durkin & Dowling, 2003). Rossi et al. (2013) reported that even
when the population investigated had apparent anatomical similarities, there were still errors within the indirect measures.

Direct measures of BSIP were first developed using estimation methods from a small population of elderly Caucasian male cadavers (Chandler et al., 1975; Clauser, McConville, & Young, 1969; Dempster, 1955). Direct measures from cadavers are more accurate but they lack external validity when extrapolated to other populations due to changes in body morphology and tissue make-up with preservative fluids influencing their accuracy. This is evident also when studying elite athletes, as human morphology varies between athletes from different sports and be quite dissimilar from the general population. For example, elite swimmers recorded significantly different BSIP than a representative group of the general population, and also between genders (Rossi, Lyttle, El-Sallam, Benjanuvatra, & Blanksby, 2013). Further research of other elite sport athletes that could have specific physical attributes would add valuable population information and expand the normative data bases. Also, researchers should endeavour to use a subject specific population when calculating BSIP as this will influence further calculations such as energy values that require accurate segmental information.

Accurate BSIP can be measured directly for living subjects using medical imaging technologies such as gamma-ray scanning (Zatsiorsky & Seluyanov, 1983; Zatsiorsky et al., 1990) and MRI (Cheng, Chen, Chen, Lee, & Chen, 2000; Martin, Mungiole, Marzke, & Longhill, 1989). Medical imaging technology is not commonly used due to limited access, expense and exposure to radiation. However, a more accessible imaging tool that is used clinically to measure body composition and bone density is DXA. Scanning with DXA is an accurate, relatively cheap, non-invasive and fast alternative method that exposes the person to low levels of radiation (Durkin, Dowling, & Andrews, 2002; Rossi et al., 2013).

Durkin et al. (2002) showed that calculating the DXA measures of length, mass, COM location and moment of inertia are accurate and repeatable. Similarly accurate results for DXA scanning were found by Rossi et al. (2013), who validated BSIPs using DXA by comparing it with indirect measurement procedures. One limitation of the DXA scanning procedure is that the scan results are in 2D, so it is unable to calculate COM position in the sagittal plane or the moment of inertia about the longitudinal and transverse axes (Durkin et al., 2002; Rossi et al., 2013).
2.4 POLE VAULT KINETICS

Technological improvements continue to provide scope for advanced research and experimentation methodologies. While ground reaction forces have been studied for some time, the pole vault has not been examined in detail. The 3D ground reaction forces and moments that are applied to the pole plant box could potentially provide new insights into the event. Being able to calculate how the interaction between a pole vaulter’s movement patterns and how they relate to the resultant kinetic profile; would enable more effective recognition of technique inefficiencies within the pole-vaulting manoeuvre.

Ground reaction forces (GRFs) have been investigated across athletic events such as running (Hamill, Bates, Knutzen, & Sawhill, 1983; Munro, Miller, & Fuglevand, 1987; Novacheck, 1998) and field events such as long and triple jump (Perttunen, Kyrolainen, Komi, & Heinonen, 2000; Seyfarth, Friedrichs, Wank, & Blickhan, 1999). The GRFs found in these studies have provided valuable information on the typical schematic representation of the force components and how they can be related to optimising performance or efficiency in these activities. However, there is a paucity research which explores the ground reaction forces of the pole in relation to performance and there is a need for further investigation.

Different interactions of the two vaulters with their poles were compared during two stages of the vault and results indicated that two different strategies of interacting with the pole achieved similar jump heights (Arampatzis et al., 2004; Schade et al., 2004). The two different strategies were related to the time that the pole-vaulter applied force to the pole during the event. Hence, two athletes achieved the same results but interacted with the pole completely differently (Schade et al., 2004). One athlete applied greater force to the pole during bending, which resulted in greater EPE in the pole; but, then applied less added energy in the later phase of the vault. The second athlete achieved the same final energy despite having created less EPE in the initial phase, but added greater energy to the pole when it was recoiling. Without including any GRF measures or the characteristics of the specific poles used, conclusion of why the athletes achieved the same height with different techniques is not comprehensive.

The GRFs produced at the base of the pole for seven pole vaulters were studied with one vault analysed for each vaulter with best heights ranging between 4.70 to 5.55m (Morlier & Mesnard, 2007). However, again the pole dynamics were not investigated.
which meant that no energy flow results were examined. This investigation provided no statistical evidence but presents a basis for further research considering reproducibility of the parameters, comparisons of elite vaulters as well as vaulter/pole and energy interactions.

In a study of six male pole vaulters, the timing of the pole plant was manipulated to examine the effect on the energy levels achieved in the pole vault (Schade & Arampatzis, 2012). This study used a training drill where the vault was not completed. Therefore, the results should be considered with caution. Grip heights and pole stiffness ratings remained constant in order to group the trials together. It was reported that increased energy was transferred to the pole from the vaulter/pole interaction, and was not due to any additional energy produced by changes in pole plant time. This increase in energy was counteracted by a simultaneous and similar decrease in the pole-vaulter energy at different phases which meant that the overall energy remains the same. It was concluded that the work of the GRFs at the base of the pole, and the strain energy of the pole, compensated for each other. These parameters need to be repeated during a fully completed vault to provide an adequate rationale for coaches/researchers to advise the optimal action for competitive pole vaulters.

A pilot study was conducted to measure changes in GRF profiles for one elite male pole vaulter using different approach run-up lengths. Results showed that longer approaches resulted in higher pole-vaults. (Doyle, Warburton, Lyttle, James, & Alderson, 2011). The 3D force profiles showed that they could be used for determining phases within the vault. It was concluded that an analysis of the GRF profiles in the pole-plant-box could assist in determining/monitoring critical variables associated with successful pole vaulting, and this needs further investigation utilising greater subject number and across experience levels (Doyle et al., 2011). Analysing the impulse is possible by giving a force profile over time, and combining that with the body position and energies at both discrete points in time, and also throughout the vault. This is essential to the understanding of vaulting mechanics which allows for more effective technique prescription and improvement.

2.5 SUMMARY

In summary, the study of pole vaulting has become increasingly technical through the development of modelling techniques, motion analysis and more recently the introduction GRF analysis. However, through limitations in design and previous
methods, currently an investigation inclusive of all aspects of the pole vault event and determining variables to performance does not exist.

While previous studies have focused on particular methods there is limited understanding of the relationship between the pole and the vaulter. Implementing 3D tracking of an athlete (with subject specific body parameters), a more complete understanding of ground reaction forces at the base of the pole as well as the pole dynamics will provide greater comprehension of the pole vault event and ultimately identify inefficiencies and improve performance.
Extended Methods
3.1 INSTRUMENTED POLE PLANT BOX

The instrumented pole plant box was designed by the Western Australian Institute of Sport (WAIS) to allow the transmission of the three-dimensional (3D) forces from the pole plant box directly through to a 3D load cell (Figure 3.1). The full dimensions of the manufactured pole plant box were within the specifications listed in the IAAF Track and Field Facilities Manual (IAAF Track and Field Facilities Manual, 2008). The only difference from a typical pole plant box was that the instrumented pole plant box incorporated a separate front and back section. The two sections of the pole plant box had a 1mm isolation built in between the two sections to allow for force transmission through to the load cell (Figure 3.2). The back section of the pole plant box, where the pole connects at pole plant, was manufactured with both a mirrored training blank and an instrumented component. This allowed the measurement of forces when installing the instrumented box; with this section replaced with the training blank when not being used for testing; therefore preventing any damage to the system.

The load cell installed within the instrumented pole plant box for the analysis of ground reaction forces (GRF) in pole vaulting was an ATI Theta-S1-2500-400 (ATI Industrial Automation, Apex, USA). The 3D load was connected directly to in-house and custom-built DAQ software to allow the recording of the 3D kinetic values over a fixed epoch and the registration of the force-time curves for display. A light emitting diode (LED) was connected to DAQ software to enable a visible light to be triggered at the start of data acquisition for alignment of the kinetic with video data. The data acquisition rate was set at 500Hz. This set-up allowed the collection of the 3D forces within pole vault through a relatively non-invasive set-up.

3.2 THREE DIMENSIONAL LOAD CELL CALIBRATION

With the introduction of calculating 3D GRF at the base of the pole in the pole vault, installing a load cell or force/torque sensor beneath the plant box is necessary. Load cells are generally used to measure the magnitude, position and direction of the GRF applied to an action, for example the foot in the stance phase of walking (Hall et al., 1996) and are an integral part of any gait analysis (Besser et al., 1993). Their functions are now being transferred to other areas of biomechanics.
Until recently there had been no studies directly linking the kinetics and energy calculations in the pole vault event. With the obvious theoretical link between the resultant pole kinetics and strain energy storage within the pole vault event, further research is needed into this area. The direct measurement of the resultant pole force in the pole plant box throughout the vaulting phase via a load cell is a necessary pre-requisite. For any calculation of forces...
to be valid it must be a true representation of the applied force (Hall et al., 1996) and therefore a calibration of the instrument is necessary to ensure confidence in the results, as it is possible that recorded errors could be due to a poor calibration. Besser et al. (1993) describe the calibration of piezoelectric force plates when a set of stairs are positioned on top and the importance of calibration being conducted in situ. It is possible that large errors could be introduced with the modification by addition of equipment such as stairs and so there is a need for evaluation of their effects (Besser et al., 1993). This is reflected within the pole vault scenario where forces are required to be transmitted through the pole plant box into the 3D load cell. It is also imperative that the load cell and plant box setup is isolated from the surrounding area to allow a valid force recording.

The load cell installed by WAIS for the analysis of GRF in pole vaulting was mounted onto a base plate which is then bolted into the ground. A 16mm thick square plate was also attached to the top providing a plate that the plant box can then be mounted onto (Figure 3.3). The load cell system has been manufactured so that it is portable allowing for the removal of the load cell for calibration. Prior to the experimental studies, the load cell was calibrated. This occurred statically before each testing session, to determine the load cell's response to a steadily applied force, and dynamically, to determine the frequency response to an impact type force.

### 3.2.1 Static Calibration

The calibration procedures were conducted at the indoor pole vault training facility in Perth, Western Australia. For the vertical axis (Z) calibration the load cell system is placed flat on the ground and weights added on top. For calibration of the other axes a wall mount set up was constructed at the WAIS. The calibration mount was bolted to a wall girder (Figure 3.2), the load cell is then bolted securely onto this mount so that the anterior-posterior (X) and lateral (Y) axes become vertical. This allowed the load cell to be elevated and rotated so that weight can be applied in the required direction on the load cell, negating the need for any complicated methods of applying horizontal loads. Another 16mm metal plate (Figure 3.3) was bolted onto the top of the load cell for the calibration procedures; this has a circular pole protruding out of the middle that the weights will remain in position. Five certified weights of 20kg were used to conduct the calibration. The load cell was
connected to an amplifier and computer running the force collection program to collect the force data.

Figure 3.3. The load cell with the base and top plate attached; metal plate attachment for weight support.

Initially, a zero measure was taken with no weight added, with 20kg weights were added one at a time up to a total of 100kg. Once the vertical (Z) axis was completed the load cell was then bolted to the mounted calibration rig (Figure 3.4) in the two orientations that allow the anterior-posterior (X) and lateral (Y) axes to become vertical. When the load cell is secured to the mounting, and checked that it is vertical, the weights were then added in the same method; 20kg at a time up to 100kg. Figure 3.5 shows the sequence of applying weights to the load cell with each weight being one trial and recorded for five seconds.

Figure 3.4. The calibration mount bolted to wall girder; set up for anterior-posterior (X) and lateral (Y) calibration.
Figure 3.5. Vertical (Z) calibration weight adding sequence, 20kg weights up to 100kg.

This data was then inputted into a computer software program (WaveMetrics IGOR Pro 6) where the mean of the five second period was calculated. The load cell output was then plotted against the known weight to calibrate the load cell. It can be seen (Figure 3.6) that the load cell response exhibited good correlation with the applied loads in all axes (b=1.010, 1.014 and 1.015) and linearity (R²=.999) over the range of measurement.
Figure 3.6. Static calibration of the load cell in the anterior-posterior (X), lateral (Y) and vertical (Z) direction.
3.2.2 Dynamic Calibration

The dynamic calibration was conducted in the Physics Laboratory at The University of Western Australia. For the dynamic calibration the response to a short impulse with a soft hammer was examined in the vertical and horizontal directions. The load cell was set up in a number of different configurations to observe the effect of the weight of the plant box. Measurements were taken for the load cell itself without added components of the plant box on it; with just the steel plate that the plant box bolts onto; and with the complete setup of the plant box in place. Repeated five second trials were recorded and the data transferred into IGOR Pro (WaveMetrics IGOR Pro 6) software to be analysed.

![Figure 3.7. Load cell dynamic response characterisation.](image)

The load cell behaves like a damped mass-spring system which can be well characterised by the resonant frequency \( f_0 \) and mechanical Q (quality factor). The manufacturers quoted resonant frequency of 820 Hz (vertical) and 680 Hz (horizontal) is reduced through the additional weight of the plant box to the load cell (F/T Transducer Installation and Operation Manual, 2014). The load cell frequency-response is shown in Figure 3.7. The higher frequencies \( f_0 = 170 \text{ Hz, } Q = 9 \) is that of vibrations in the vertical direction, while the lower frequency \( f_0 = 25 \text{ Hz, } Q = 8 \) is in the horizontal planes. Limited effect will occur on the load cell response in the horizontal plane \((x,y)\) at loading frequencies below approximately 10 Hz, after which, the resonant characteristics will affect the signal according to the transfer function shown. Similarly, in the vertical direction \((z)\) the load cell response is flat for frequencies below 30 Hz. Post-collection filtering of the time-series force data will substantially reduce the peaks in the response curves (Figure 3.7).
3.3 POLE BENDING SYSTEM DEVELOPMENT

Pole vault poles are typically characterised by the manufacturers using simple summary variables related to the how stiff the pole is, the length and diameter of the pole and a safety load rating. These summary variables do not provide the level of information required to quantify the elastic energy absorption and conversion potential and load deformation properties. A component of this research involved the design and development of a pole bending system for the collection of information on pole bending when subjected to loading. There is limited published research on pole deformation and its characterisation. The development of such methods was a focus of this research. The characterisation of the pole vault poles were addressed using data collected from the completed system on the specific poles used in the experimental trials.

Initial planning and development commenced in late 2011, through cooperation between the Schools of Physics and Sport Science, Exercise & Health at The University of Western Australia and the WAIS. The design work and manufacturing processes were conducted at the School of Physics. The focus of the initial design was to develop a system that could control the pole bending while recording the load applied and the amount of bend produced in the pole. Through continued development and consultation with laboratory technicians the designs produced a system that provided the author with a means of analysing and characterising the pole vault pole beyond their manufacturer ratings. A transverse (birds-eye) view of the system during testing in Figure 3.8 and the initial plans for the system are shown in Figure 3.9.

Figure 3.8. Transverse (birds-eye) view of the pole bending system during load-deformation testing.
Figure 3.9. Initial designs diagrams for the pole bending system.
From the initial designs some minor improvements were made during the development that improved the mounting of the load cell (Figure 3.10a) and also the trolley wheel design (Figure 3.10b). The system consisted of an electric winch, 3D load cell, a 6m steel truss as a guide track and a trolley designed to run along the track connected to the winch. A 12V 3000lbs Electric ATV winch was mounted to a solid steel frame that could then be bolted to one end of the guide track.

The load cell was mounted securely to this frame immediately in front of the winch so that the winch was pulling toward the load cell. The winch cable was used to pull the trolley along the guide track to compress the pole between the load cell and the trolley. To stabilise the trolley, 4 tracking wheels secured around the sides of the track limited any lateral or vertical movement.

Hollow steel sleeves were used to pivot the pole at each end (one attached to the load cell and one on the trolley as seen in Figure 3.10b) and control the direction of the pole bend. This sleeve fitted over the end of the pole vault poles and ran 5cm along the pole. The design of the sleeves meant that forces applied to the poles at each end were distributed around the end of the pole therefore minimising point loads that can cause damage. Each sleeve was attached to the steel frame using a single pivot bolt that could rotate to 90° and that restricted all movement in planes other that the horizontal where the pole was required to bend.
All machining of the components in the system was conducted by technicians at the School of Physics. This involved the welding and construction of the winch mount and trolley and also the machining of the trolley wheels and pole sleeves.

A steel tape measure was positioned at the end of the track opposite the winch and connected to the trolley. A Sony digital video camera was set above the tape measure to record the trolley movement and therefore the change in pole length. Within the field of view of the camera was a LED synchronisation light, this light was connected to the force plate control box and is initiated whenever the load cell started recording. Through capturing the LED light and the trolley position, the force and displacement could be synchronised together. Measurement of the applied load was performed using the 3D load cell connected to an in-house purpose built computer data acquisition (DAQ) system. The videos were analysed by digitising the displacement on the measuring tape and the time using video analysis software (SiliconCoach Pro 7.0). The force and displacement data was then combined and analysed to determine the load-deformation curve.

### 3.4 BODY SEGMENTATION PROCEDURES

The methods for body segment inertial parameter (BSIP) calculations were based on those developed and reported by Rossi et.al. (2013). Full body dual-energy X-ray absorptiometry (DXA) scans were conducted on each participant at The University of Western Australia. The DXA scan evaluated the areal density (mass per unit area in the frontal plane) and the mass associated with body tissues (bone, fat and lean tissue). The participant laid on the DXA platform (Figure 3.11a) within the scanning area; feet shoulder width apart with forearms in neutral position. The scan lasted approximately five minutes and scanned the whole body in one process exposing the participant to a radiation dose of ~0.8 μSv.

![Figure 3.11. (a) The DXA scanner; (b) The Artec L™ 3D scanner.](image)
Three-dimensional surface scans of the participants were captured using Artec L™ 3D scanners (Artec, TDSL) and from these, anthropometric measures were calculated (Figure 3.11b). The scanners project a mesh of dots onto the body surface and then capture images of them with a video camera. The mesh light projector and the camera are calibrated relative to each other (raster-stereography). The mesh is captured at 15 frames per second, with a resolution of up to 1mm and 3D point accuracy of up to 0.2mm. The scans were captured and processed using Artec 3D Scanner v0.6 software. The same software was also used for the post-processing, this involved finer alignment of the scan frames, filling any holes, cleaning unnecessary scanning and smoothing the surface to create a 3D model of the whole body (Figure 3.12).

![Figure 3.12. Example of a 3D whole body scan.](image)

The anthropometry measures needed as inputs into the body segment inertial parameter methods were gathered from the 3D scans for all subjects. These include the heights, lengths, breadths and girths for specific body segments, these measures followed the same protocol as in Rossi et.al. (2013). The anthropometric measures are then calculated within the Artec software through manual location of body landmarks and using the inbuilt functions available.

Mass data was extracted directly from the generic DXA enCORE® software (version 8.50.093, GE Healthcare, 2004) made available from the manufacturer for internal and non-commercial purposes only. This method was previously adopted to analyse body segment inertial parameters of elite swimmers (Rossi et al., 2013). The software...
displays two data matrices from the DXA scan; mass data for the bone mineral density (BMD) and the mass data for the tissue compartment which includes extracellular fluids and solids, total body water, intracellular solids and fat. The matrices are divided into rectangular mass elements with dimensions of 0.51cm (transverse) x 1.54cm (longitudinal). Each element represents a section within the entire scanned area and the summation of the matrices provided the whole body mass. The process of allocating mass to each element was taken from Rossi et al. (2013); where data from the two matrices were co-registered with their respective greyscale images (8-bits bitmap files, resolution of 72 DPI) and exported by the scanner software (Figure 3.13).

Figure 3.13. The BMD, Tissue and Total mass images from the DXA scan.

There is a linear relationship between the shade of a given pixel and the areal density of the region represented (greater mass as the shade become whiter). This process is described in Rossi et al. (2013). A Matlab® (Ver. 7.8.0.347) code was written to manually digitised the segments from the DXA image; this then calculated the mass and COM of each segment (Figure 3.14).
Figure 3.14. Segmenting of DXA image in Matlab.

The anthropological measures from the 3D scans provided all the necessary inputs for the indirect measures to calculate the mass and centre of mass (COM) for each segment. The five indirect estimation methods used were the same as those outlined in Rossi et al. (2013):

The Modified Chandler (Chandler et al., 1975) method (C) uses simple linear relationships between the total body mass and separate segment masses; with the COM position as a fixed ratio of the distance from the COM to the proximal joint of the segment, and the length of the segment. These relationships were based on cadaveric data collected on six males.

The second was the Modified Yeadon (1990) method (Y), which is a geometric method using cylindrical and stadium-shaped solids to represent body segments. To calculate BSIPs, the geometrical shapes are assigned a uniform density value based on cadaveric data (Dempster, 1955). And then the mass, centre of mass and moments of inertia of each solid were computed from the provided equations (Yeadon, 1990).

The third method was a Simple Regression Method (Z1) proposed by Zatsiorsky and Seluyanov (1983) which only uses the whole body mass and height as predictors for each of the BSIPs. All three Zatsiorsky methods were based on 100 young adult Caucasian males.

The forth method was the Zatsiorsky Multiple Regression Model (Zatsiorsky and Seluyanov, 1985) (Z2) was derived which uses up to four local anthropometric measures (i.e., segment lengths, breadths, girths and diameters) of each segment as
predictors in linear equations, as inertial parameters of a given segment are expected to correlate better with the anthropometry of that segment rather than global measures like body mass.

The fifth method used was the Zatsiorsky Geometrical Model (1990) (Z3), which assumes each segment to be a circular cylinder; and uses a segment-specific, quasi-density value calculated to minimise differences between the cylinder and the real segment volumes. Zatsiorsky et al. (1990) claimed that this geometric model can estimate the BSIPs of groups not necessarily matching the anthropometry of the cohort used to derive the equations.

3.5 POLE VAULT DATA COLLECTION
All data collection was conducted at an indoor training facility that is commonly used for training sessions and is equipped with a full length undercover runway that has been surveyed and certified to meet with IAAF standards for competition. With a roof height greater than 8 meters the facility is perfect for pole vaulting and providing more consistent environmental conditions. Pole vault jump data collection was conducted over multiple testing days and had to be scheduled around athlete availability and training requirements. The testing days for all athletes were scheduled to match their training level where possible, diet and prior activities were not controlled for except that athletes were advised to prepare as they would a normal training session. Each testing session was structured as a normal training session with the athletes resting between jumps and manipulating the conditions of each jump as they would for training. This allowed the athlete or coach to determine the bar height and stand position as normal and also change the pole they were using as necessary.

Prior to the data collection the vaulters were required to do their normal warm ups to their satisfaction which could involve practice jumps from a shorter approach. There was no set minimum or maximum number of jumps required, the session time was determined by the vaulter themselves or their coach. Only full approach jumps were analysed although all attempts were recorded. The vaulters jumped on the poles that they would normally use and the timing when they changed pole was at their discretion. Variables recorded for the jump included; bar height, stand position, pole manufacturer, pole length, pole flex and grip height. Notes were also taken to include if the jump was successful and if there was anything that occurred that could potentially preclude the trial from analysis. At no time were the participants instructed by anyone other than
their coaches on the equipment or technique used so that the data recorded was not
influenced.

The pole vault pit was fitted with a 3D instrumented pole plant box to enable the
collection of GRF at the base of the pole (Figure 3.2). This pole plant box set-up
consisted of a plant box that aligns with IAAF requirements, which is bolted securely to
a 3D load cell, which in turn is bolted into the ground. This does not affect the vaulters
in any way as the plant box is still exactly the same and the load cell is concealed. The
load cell is the same one used in the pole bending trials. The force was recorded for a
five second period that enveloped the jump. For synchronisation of the force recordings
a sync light (LED) was connected to the force control box and positioned near the
vaulters take-off position. This light would turn on when the force recording began and
the switch off at the end of the five second trial.

Historically, pole vaulting mechanical analyses has been conducted using planar two-
dimensional (2D) video analysis (Zagorac, 2013; Linthorne & Weetman, 2012) with a
small number of 3D analyses conducting using two cameras views to manually derive
the 3D joint trajectory data centre (pseudo 3D biomechanical models that rely on 2D
vector based body segment models) (Arampatzis et al., 2004; Schade et al., 2004;
Morlier & Mesnard, 2006). However, the initial drawback of these approaches is that
single and two camera 3D approaches are associated with increased modelling error in
the form of joint angle cross-talk, especially when the movement plane occurs across all
three planes (Ackland et al, 2009). While, participant compliance precluded the use of
marker based tracking systems, we adopted a six camera approach (> four shown to be
optimal) to derive the trajectory data for the resulting 3D kinematic analysis. This
facilitated improved accuracy in the kinematic data (joint angle, velocity and
acceleration) required as an input parameter for the energy flow estimation of interest.
Figure 3.15 depicts the camera positions employed for the data collection. Conducting
the data collection indoors allowed the mounting of three cameras on the walls
surrounding the vaulting area. A large hanging curtain was erected as a uniform
background allowing greater accuracy during the digitising process. Figure 3.16 shows
each of the six camera views that were used to capture the jump. Four of these cameras
were set up for synchronised high definition recording through nano-flash recorders that
converted the video into standard definition at 25 frames per second. Cameras five and
six recorded individually in standard definition to be synchronised post testing.
Figure 3.15. Representation of the camera positions for pole vault data collection.

All cameras had the LED sync light and reference point within their field of view so that all videos could be matched to the force trials. The field of view for all cameras was set to be as small as possible while including two steps prior to the take-off, both upright bar stands and approximately one meter of clearance above the height of the bar in order to see the complete vault (Figure 3.16).

Calibration of this testing volume involved positioning a 3D rectangular prism (Figure 3.17) of dimensions 3x2x1 metres in five different locations to capture the entire volume that the vaulter travels through. Included in each camera’s field of view was a reference point that is used to position the calibration in all of the digitisation trials. This calibration procedure was then repeated for each testing session.
Figure 3.16. Screenshots from all 6 camera views.

Figure 3.17. Example placement of the calibration cube

Table 3.1. Participant details.

<table>
<thead>
<tr>
<th>Vaulter</th>
<th>Gender</th>
<th>Age</th>
<th>Jumps</th>
</tr>
</thead>
<tbody>
<tr>
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<td>22.8</td>
<td>8</td>
</tr>
<tr>
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<td>Male</td>
<td>16.5</td>
<td>9</td>
</tr>
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<td>3</td>
<td>Male</td>
<td>30.6</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>26.8</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Female</td>
<td>28.8</td>
<td>8</td>
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<tr>
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<tr>
<td>8</td>
<td>Female</td>
<td>16.1</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.1 shows a total of 67 vaults were recorded across all eight participants, although not all participants recorded the same number of vaults. For each vault there were six different camera views and the force profiles recorded. All 3D video analysis was
conducted at 50Hz using Ariel Performance Analysis System (APAS 2000) manual digitising software.

Calibration of the capture volume for each testing session was first conducted. From the five locations of the calibration cube, 30 calibration points of known coordinates that encompassed the vaulting volume were selected. Each of the 30 points were visible in all six cameras in order to create a 3D reconstruction of the volume. The points were digitised in each of the camera views along with the reference point. The coordinates for each point was manually inputted into the program and then this calibration was loaded into the relevant vault trials for that session.

For each vault trial the six video files were loaded into the APAS Trim module to be synchronised and trimmed. The camera views were synchronised together by finding the field in the video that the LED light first appeared. The videos were trimmed to approximately before the touch down for the penultimate foot strike and 20 fields past the peak height, this generated a video ranging between 104 and 126 fields. This was to guarantee that the whole vault was digitised and to allow for filtering end effects in the data. Once the trimming was completed the videos were saved and could be loaded into the digitisation module.

Each participant had a sequence file created for them within the APAS Digitise module. This contained information including their height, mass, the points used for digitising, the segments created by joining these points and the calibration for that session. Eighteen landmarks on the body were digitised along with the top of the pole and the top hand grip position. Within the APAS software each digitised point was connected to the necessary proximal or distal points to create the body segments. End point digitising was conducted where each of the landmark points was digitised in all frames.

Once the digitising of a trial was complete in each view they were transformed to create a 3D reconstruction of the digitising; this was done in the APAS Transform module. Once the 3D file was created it was filtered within Filter module by running a digital filter at 5Hz. This frequency was selected based on the segmental movement speed within the vault as displayed within the APAS filtering power spectrum curves. The raw and filtered data was then outputted for further analysis.
A custom designed data analysis program was written in IGOR Pro (WaveMetrics IGOR Pro 6) software (Appendix) to conduct all further analysis of force and digitised data. This program is where all data collation and analysis was conducted. Several individual programs were written to initially deal with the pole, force and video data separately and then the relevant sections were brought together for the final analysis. The program was written so that all of the energy calculations could be conducted while varying the input data. This allowed the six methods of BSIP outlined earlier in this chapter to be used in the same program interchangeably. Statistical analysis was conducted from the analysed raw data in the IGOR software program; these methods are further explained in the respective following chapters.
The Dynamics of the Vaulting Pole
**4.1 INTRODUCTION**

Effective performance in the pole vault event is heavily reliant on the efficient transfer of energy throughout the vaulting phase. Key to this energy transfer is the storage and recovery of the elastic potential energy (EPE) in the pole. This transfer of energy by the pole is vital for the athlete to convert their initial kinetic energy (KE) from the approach into gravitational potential energy (GPE) in order to clear the bar. Research investigating the pole vaulting technique has traditionally examined the pole and vaulter in isolation. Pole investigations have concentrated on modelling the pole structure and bend (Burgess, 1998; Ekevad & Lundberg, 1997; Griner, 1984; Jahromi et al., 2012). Whereas, research primarily aimed at investigating the vaulter dynamics have simply relied on assumptions about the poles behaviour and have not considered variable poles bending behaviour (energy storage and recoil). The energy stored in the pole is a more recent area of vaulting scientific analysis where significant advances can be made to incorporate specific pole characteristics into the overall energy calculations.

Previous research has reported the interaction of the vaulter with the pole, inclusive of the compressive force and the bending moment applied by the vaulter (Schade, Arampatzis, & Brueggemann, 2004). This illustrates how a vaulter is able to transfer energy into the pole and highlights the complexity of the energy transformation in the pole vaulting technique. Griner (1984) investigated the manner by which a pole vaulter applies the bending moment, with the aim of identifying an optimal technique to load the pole and subsequently gain greater energy from the recoil. However, this research did provide a calculation of the energy stored within the pole. With the overall outcome in pole vaulting being to achieve maximal jump height, a complete analysis of the strategies employed must incorporate the quantification of pole specific energy storage and loss.

A pole vaulter’s personal pole selection preference is likely based on their personal strength, power, technique and familiarity with the pole model itself. Modern poles are typically distinguished by the manufacturers using a length, weight and generic stiffness rating. Poles are designed with a *pre-bend*; a partial bend induced during manufacturing that allows the vaulter to control the direction of bend and also lessens the initial impact at pole plant, although there is no research to quantify pre-bend information. A vaulter will transition through multiple poles during a training session and competition; where they will initially start with a softer pole (higher flex rating) and progressively move to
a stiffer pole (decreased flex) as the height of the bar is increased. The methods used to determine the manufacturer’s generic stiffness and weight rating are derived by a static test of deflection under load to express the relative stiffness of each pole. However, this variable is not typically calculated in a manner that represents the pole’s dynamic behaviour during the vaulting manoeuvre. These static loading tests involve the assessment of beam deflection when a pole is supported at each end with a span that can be different depending on the manufacturer. A mass is then loaded at the centre of the span and the deflection (in cm) is referred to as the flex rating. This flex rating is then used to assign an approximate weight safety rating to the pole yet how a bending pole behaves as a column as opposed to a beam may be dissimilar (Beer, Johnston, & DeWolf, 2006). To increase the validity of a pole’s stiffness rating the pole should be tested using a method that more accurately reflects the pole’s position and dynamic bending behaviour during a vault.

The introduction of load cells placed at the base of the pole plant box to record pole ground reaction force (GRF) has facilitated the estimation of stored pole energy. By assessing the change in length of the pole and the pole GRF the energy in the pole can be calculated and this figure can then be included in equations quantifying total energy transformations throughout the vault. However, this method of calculating the stored pole energy does include assumptions about how the pole is behaving during dynamic loading. Primarily, this method doesn’t account for the energy loss in the pole exhibited during recoil; thereby limiting the effectiveness of the method to describe the energy contributions throughout the entire vault. This limitation also inhibits the validity of pole to pole comparisons given the likely significant variation in individual pole energy storage and recoil characteristics.

The aims of this preliminary investigation are primarily descriptive. The first is to quantify if pole bend is linear and to assess the accuracy and relevance of manufacturer pole stiffness ratings. The second aim is to investigate if the pole bending methodology employed can alter the calculated pole energy storage values. Finally, this study sought to develop a more rigorous and valid pole elastic energy assessment method for incorporation into the total energy calculation of an entire vault.

It was hypothesised that load-deformation characteristics of poles would display non-uniform bending properties. The method of pole bending assessment would affect the
calculation of the elastic energy stored in a pole with the slow dynamic measure providing higher storage capabilities compared with the quasi-static. It was further hypothesised that the energy loss through the pole in bending would be higher using the slow dynamic pole bending compared with the quasi-static.

4.2 METHODS

4.2.1 Equipment/Instrumentation
A custom designed bending system was used to conduct the pole testing. The development of this bending system is detailed in full in Chapter 3.2.

The poles used in the data collection were either 1) the specific poles used by the athletes in the vaults analysed in Chapter 5, or 2) where athletes did not give permission for their personal poles to be tested, new poles were purchased. These new poles were matched to the specific measures and ratings of those used by the vaulters. In all cases where new poles were purchased, care was taken to ensure that the correct pole manufacturer ratings and measures were obtained. These variables included the pole length, mandrel size (measure of the pole diameter) and the flex and weight ratings. Due to potential athlete safety concerns arising from any possible damage to the poles during the load/deformation testing, the poles used in this testing were discarded following this procedure. All pole load/deformation trials were photographed and filmed from above during the testing procedures using a high definition camera operating at 50 Hz, Figure 4.1 is an example picture taken from above the bending system.

![Figure 4.1. Above view of the pole bending system during load-deformation testing.](image)

4.2.2 Procedures
A total of 14 poles were analysed, 12 of which were matched to actual jumps recorded by athletes in the proceeding vaulting analysis (Chapter 5). Two of the poles were then cut from their original full length down to the grip height used by the vault in their
analysed jumps (Chapter 5). These two poles were then testing under the same conditions. Poles were acquired from three different manufacturers who utilise different materials in construction. Poles from Manufacturer A are a fibreglass based construction, Manufacturer B a carbon fibre construction and Manufacturer C, a composite construction of fibreglass and carbon fibre.

When a pole is manufactured it is distinguished by its manufacturer ratings, being the pole length and the flex and weight ratings. The tester was blinded to the manufacturer ratings at the time of testing however the manufacturer details were recorded post-testing. The flex rating of all poles were reassessed in the laboratory compared with the original manufacturer value. To measure the flex of a pole of length $L$, it is supported using a point couple with the supports positioned 30cm from either end of the pole as shown in Figure 4.2. The deflection at the centre is first measured from the height of the stands in an unloaded (no attached weight) situation to ascertain pre-bend. Measurements were taken from a level box above the pole to the top of the pole at the centre. A 50lb (22.7 kg) weight is then suspended from the centre of the pole and the change in displacement is measured from the pre-bend position to this weighted position is given as the flex rating.

![Figure 4.2. Testing setup for replication of pole flex measurement.](image)

A custom designed bending system was used to conduct the remainder of the testing (design details in Chapter 3.2). This system consisted of a three-dimensional (3D) load cell mounted to one end of a six metre long steel track. An electronic which mounted behind the load cell was connected to a running trolley at the other end of the track. The pole was compressed between the load cell and the trolley with the direction of pole bend controlled using pivoting sleeves that the pole fitted into on each end. A Sony digital video camera was set above the tape measure attached to the trolley to record the movement and therefore the change in pole length. Within the field of view of the
camera was a light-emitting diode (LED) synchronisation light, this light was connected to the force plate control box and is initiated whenever the load cell started recording. Through capturing the LED light and the trolley position, the force and displacement could be synchronised together. The pole testing procedures were conducted over multiple testing days in a large open indoor area. All environmental conditions were recorded and the temperature remained between 19.2-23.7° across testing sessions.

Each pole was subjected to a quasi-static and slow dynamic testing protocol on the bending system. The quasi-static protocol involved the poles being compressed in small increments and then the force measured statically at each point. The winch was turned on and then off again to compress the pole a small displacement and then hold it statically in that position. The increments were not uniform however every attempt was made to keep them consistent, with small increments initially followed by larger displacements as the pole bend increased. For each increment of pole compression, the force applied was recorded for five seconds using the load cell data acquisition software and then the pole was compressed again. Poles deformation continued until it was compressed to an equivalent maximum degree observed during pole vault trials. The process was then reversed to record the load/deformation during decompression while the pole returned to its fully extended resting position. Approximately 25 increments were recorded for compression and again for decompression, with the load registered using the load cell at each recorded deformation distance.

The slow dynamic protocol followed a similar procedure to the quasi-static except that the compression and release was performed in a continuous sequence. The pole was compressed up to the desired displacement point then a controlled continuous release commenced immediately. This created full compression and release trials lasting between 40 and 60 seconds, in which the force was recorded and matched to the displacement determined from the video of the trolley position. The force trials were temporally synchronised to their respective video using LED light which coincided with the kinetic data collection. This allowed the deformation changes to align with the loading value recorded by the load cell. Approximately 80-100 displacement points were digitised from the dynamic videos.
4.2.3 Data Treatment
The videos were reviewed using video analysis software (SiliconCoach Pro 7.0) and for the quasi-static trial each of the force measures was matched to a displacement measure taken from the video. For the dynamic trials the times of the displacement measures were matched to the time in the force trial to provide load-deformation data.

Force and displacement time varying datasets were input into a custom analysis program written in IGOR Pro (WaveMetrics IGOR Pro 6) software for further analysis. For tests of linearity of the load-deformation data an R-squared ($R^2$) was computed for each pole under all bending conditions. A paired sample t-test was performed to determine statistical significance between the quasi-static and dynamic bending methodologies with significance $\alpha <0.05$.

4.3 RESULTS AND DISCUSSION
4.3.1 Pole Specifications
A manufacturer flex rating is a single number designed to distinguish between poles, though rating scales are not typically standardised between manufacturers. Table 4.1 outlines the range of poles used by the vaulters participating in this research (Chapters 5, 6 and 7). The flex rating is the original manufacturer provided rating and measured flex is an attempt to reproduce this same rating using the standard deformation loading methodology (section 4.2.2 above).

For Table 4.1, the poles from Manufacturer A are a fibreglass based construction, those from Manufacturer B are a carbon fibre construction and Manufacturer C are a composite of fibreglass and carbon fibre. Pre-bend measurements consistently ranged from 2.2-3.0cm across the 16 poles assessed. The measured flex ratings were similar to those reported by the manufacturer however they did not directly reproduce the same values (measurements were between 0.1cm and 2.8cm different to the manufacturer ratings) and the variation from the measured value was inconsistent (non-linear). Given the lack of clarity from the manufacturers surrounding their testing set-up, it is uncertain if the variations exhibited in these results are due to changes in pole elasticity over time and use, systematic tolerances of the manufacturer’s set-up or the current study’s replication set-up. Notwithstanding, all attempts were made to ensure the current testing set-up provided controlled and accurate recordings of each pole’s static loading displacements. From a practical application perspective, coaches and athletes heavily
rely on the accuracy of the manufacture flex rating for pole selection. Given that the current study was unable to reproduce manufacturer ratings, a more detailed characterisation of poles and their characteristics is indicated.

Table 4.1. Characteristics of tested poles; length (m), weight rating (lb/kg), manufacturer flex rating (cm), measured flex and measured pre-bend. Poles 15 and 16 are poles 11 and 3 respectively, reduced to the grip length used in the dynamic trials. Poles 1 and 4 were measured experimental poles excluded as they were not used in this analysis.

<table>
<thead>
<tr>
<th>Pole Number</th>
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<th>Length (m)</th>
<th>Weight Rating (lb/kg)</th>
<th>Flex Rating (cm)</th>
<th>Measured Flex (cm)</th>
<th>Measured Pre-bend (cm)</th>
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<td>16.0</td>
<td>17.9</td>
<td>2.7</td>
</tr>
<tr>
<td>14</td>
<td>A</td>
<td>4.90</td>
<td>200/91</td>
<td>15.4</td>
<td>15.9</td>
<td>2.9</td>
</tr>
<tr>
<td>15</td>
<td>C</td>
<td>4.01</td>
<td></td>
<td></td>
<td>15.8</td>
<td>2.2</td>
</tr>
<tr>
<td>16</td>
<td>A</td>
<td>4.12</td>
<td></td>
<td></td>
<td>17.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>

It is also important for coaches and athletes to understand the effect different grip heights have on the effective stiffness of a pole. Typically pole manufacturers produce pole lengths in 0.15m increments. Variations within this 0.15m of the grip height will inherently alter the effective stiffness of the pole. In the demonstrated example of the two poles above (pole 15 and 16), large differences were observed when the poles were cut to the grip length used by the vaulter and re-tested. Through moving the supports closer together the flex rating is decreased, therefore the pole is effectively stiffer for this static load test than the original flex rating suggests. As such, when distinguishing poles, it is also important to take into account the hand grip position during the vault as this will fundamentally affect pole stiffness (real versus reported). For example a pole with lower flex rating held in the vaulter’s hand at a higher grip may feel softer than a pole with higher flex if the hand position is lowered.
The linearity of the data was tested using an $R^2$ statistic for the loading and unloading portions of the load-deformation curve using each bending regime. The results for every pole are displayed in Table 4.2. These results confirm that the load-deformation relationship for poles is not uniform (linear); indicating that more detailed analysis of the load-deformation curve is required.

Table 4.2. R-squared values for a linear fit to load-deformation curves on all poles

<table>
<thead>
<tr>
<th>Pole Number</th>
<th>Quasi-Static Loading</th>
<th>Quasi-Static Unloading</th>
<th>Dynamic Loading</th>
<th>Dynamic Unloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.245</td>
<td>0.476</td>
<td>0.339</td>
<td>0.506</td>
</tr>
<tr>
<td>3</td>
<td>0.314</td>
<td>0.403</td>
<td>0.288</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td>0.328</td>
<td>0.383</td>
<td>0.244</td>
<td>0.414</td>
</tr>
<tr>
<td>6</td>
<td>0.285</td>
<td>0.329</td>
<td>0.254</td>
<td>0.440</td>
</tr>
<tr>
<td>7</td>
<td>0.317</td>
<td>0.405</td>
<td>0.311</td>
<td>0.492</td>
</tr>
<tr>
<td>8</td>
<td>0.295</td>
<td>0.469</td>
<td>0.305</td>
<td>0.459</td>
</tr>
<tr>
<td>9</td>
<td>0.263</td>
<td>0.322</td>
<td>0.182</td>
<td>0.438</td>
</tr>
<tr>
<td>10</td>
<td>0.304</td>
<td>0.391</td>
<td>0.245</td>
<td>0.416</td>
</tr>
<tr>
<td>11</td>
<td>0.311</td>
<td>0.392</td>
<td>0.257</td>
<td>0.597</td>
</tr>
<tr>
<td>12</td>
<td>0.354</td>
<td>0.407</td>
<td>0.265</td>
<td>0.628</td>
</tr>
<tr>
<td>13</td>
<td>0.353</td>
<td>0.432</td>
<td>0.269</td>
<td>0.562</td>
</tr>
<tr>
<td>14</td>
<td>0.349</td>
<td>0.375</td>
<td>0.275</td>
<td>0.572</td>
</tr>
<tr>
<td>15</td>
<td>0.339</td>
<td>0.453</td>
<td>0.267</td>
<td>0.586</td>
</tr>
<tr>
<td>16</td>
<td>0.316</td>
<td>0.37</td>
<td>0.269</td>
<td>0.579</td>
</tr>
<tr>
<td>Average</td>
<td>0.312</td>
<td>0.401</td>
<td>0.269</td>
<td>0.521</td>
</tr>
</tbody>
</table>

4.3.2 Bilinear fitting of Load Deformation Data

As previously outlined, it is necessary to develop a pole characterisation method that can be used to minimise the pole bending assumptions used within a pole vaulting mechanical analysis. Through the production of load-deformation curves from pole bending tests it is possible to fit the curve characteristics, by way of an empirical function to the data, which will produce unique coefficients for each pole.

The data produced showed a complicated load-deformation relationship with two regions that were consistent for all poles as shown in Figure 4.3. Pole characterisation in this study was conducted using two methods, the first being a bilinear model method which is standard in the literature and the second using a modified fitting function. This bilinear approximation method of fitting has been used extensively in research of loading columns (Baza, 2010; Britvec, 1973; Dutta, 1998; Ekevad, 2006; Saliklis, Urbanik, & Tokyay, 2003). Following data inspection the bilinear method was used to
characterise the force displacement curves of the poles. This provides an approximation method and is used as a simplified representation of the curve. The characterisation with a bilinear fit applies two linear curve fits and a corner point (sometimes termed the break point) position where the linear lines intersect, whereby a simplified version of the response of the pole using four determining variables. Using the equation for linear fit (1), values for $a$ and $b$ could be calculated for the two sections of the curve.

$$y = a + bx$$  \hspace{2cm} (1)

The two regions were defined as an initial slope (Slope 1) that was very steep as the force increased dramatically for minimal displacement. A secondary slope (Slope 2) was then more gradual as it involved large displacements for smaller force changes.

![Figure 4.3. Example quasi-static data; lines of best fit to the low and high regions for both loading and unloading, corner point shown on the loading data.](image)

With this observation of the two linear slope regions it was considered that the slope of the two identified regions may be used to distinguish individual pole characteristics. Both the loading and unloading phases follow similar behaviour such that a bilinear fit was conducted on each phase for every pole. While attempting to keep the number of coefficients to characterise the pole as low as possible it remained necessary to identify other distinguishing characteristics of the curve. A ‘corner’ point at the intersection of the two bilinear fits provided final points for comparison (Figure 4.3). The location of
the corner point provides a force and a displacement measure for each pole. This bilinear fitting method provides a simple characterisation of a pole using four coefficients for loading and four coefficients for unloading (two slopes and the corner point force and displacement) which could be used to determine differences between poles.

4.3.3 Empirical Fitting Function for Pole Load Deformation Curve

For the second and more accurate method of characterising poles we applied a curve fitting function which is a modified version of published stress-strain theory. This provides pole specific coefficients that recreate the curve for each individual pole such that we can model the pole’s response allowing us to integrate up to any point of deformation. From the load deformation relationship a function was developed to improve the bilinear fit for the data from the bending trials. The fitting function was optimised to minimize the number of coefficients while also minimising the error in the fit to the data. The function chosen has seven coefficients for loading and seven for unloading and can be used to recreate the data from the displacement at the end of the pole. Equation 2 below is the resulting fitting function used to calculate the force at x displacement:

\[
\text{Force}(x) = a + b(x - x_0) - \frac{c}{(x-x_0+d)} + f(x - x_0)^g
\]  

(2)

The equation has four terms that define the fit. The first term \(a\) is a constant whose value is set by requiring the curve to pass through the origin. The second term is a linear expression corresponding to Hooke's Law. The third is a hyperbolic term and the final term is a power law empirically chosen to model the slight rise observed at higher displacements, which contributes negligibly to lower displacements. Higher terms such as the hyperbolic have been used in the literature (Duncan & Chang, 1970) and are a popular method for describing stress-strain relationships.

Figure 4.4 is an example of a pole bending quasi-static trial with the above equation fitted to both the loading and unloading curves where there is an observable difference between the two curves. Through manipulation of the coefficient values the same function is utilised in the loading and unloading. Using the IGOR program, where the fitting function was applied, a fit error was calculated. This summed the square of the difference between the actual data and the fit function. As the coefficient values were
manually adjusted this error updated such that it could be minimised to find best fit. A full listing of the coefficients is listed for each pole in Appendix C.

Figure 4.4. Example force vs displacement for quasi-static bending trial fitting for loading and unloading using Equation 2.

The energy in the pole is calculated by finding the area underneath the load-deformation curve which is equal to the integration of Equation 2. For calculation of the EPE stored in the pole as a function of displacement (x) the above function is integrated to become Equation 3 below:

\[
\text{Elastic Potential Energy}(x_s, x_f) = a(x_f - x_s) + \frac{b}{2}(x_f^2 - x_s^2) + bx_0(x_f - x_s) - c \ln \left\{ \frac{d+x_f-x_0}{d+x_s-x_0} \right\} + f \frac{x_f - x_0}{1+g} - (x_s - x_0)^{1+g}
\]  

(3)

Where \(x_s\) is the starting displacement, \(x_f\) is the final displacement and where \(a, b, c, d, f\) and \(g\) are the pole specific coefficients. This allows the energy stored in the pole to be calculated at any level of deformation, in addition the difference in the energy stored in the pole and then recovered during the unloading calculated. The energy lost can be calculated by taking the total energy for the loading curve and subtracting the energy of the unloading curve. This equation can be incorporated into a mechanical analysis of the vault where pole specific energy is calculated using the change in length of the pole.
4.3.4 Comparison of bending methods
The static tests, while providing simplified and accessible information surrounding pole bend characteristics, may not reflect pole behaviour during a dynamically loaded vault (i.e. during a real pole vault attempt). Therefore analysis of bending characteristics when pole deformation more closely replicates behaviour observed during a true vault attempt is clearly required from an ecological validity perspective. Although an exact replication is difficult due to the complicated nature of vaulter-pole interaction, we propose that the quasi-static and dynamic testing methodology (Figure 4.5) adopted in the present study has greater applicability and relevance than the current static manufacturer rating system.

Figure 4.5. Example force vs displacement for quasi-static (above) and slow dynamic (below) trial for the same pole.
The bending characteristics for the same pole using the two methods of bending show some differences (Figure 4.5 is an example pole representative of the results for all poles). Initial testing showed that dynamic forces may be greater than those recorded during quasi-static and static testing however this difference may be explained by stress relaxation within the pole over time. During a quasi-static trial the pole is bent and then rests while the force measure is recorded. This rest allows the force to settle at a load value while still holding the same amount of compression in the pole, when a pole is deformed (bent) dynamically this rest (settling) time is not available. This reinforces the position that any pole characterisation should be conducted in conditions best representing pole behaviour during an empirical vault. During a vault the athlete loads and unloads the pole in a very short period of time (less than two seconds) and therefore, while not exact, the slow dynamic method is likely a closer representation of the pole behaviour occurring during a vault.

Figure 4.6 shows the quasi-static versus slow dynamic methodology slopes for every pole. Greater standard deviations are observed in the calculation of Slope 1 (initial slope in load-deformation curve) for both loading (Figure 4.6a) and unloading (Figure 4.6c). This was attributed to the difficulty in obtaining large numbers of measurements in the first section of the bend where the force applied is increasing rapidly. The observed between method differences in Slope 1 may be explained by a time constant within the system. This time constant represents a delay in the system reaching equilibrium during the quasi static trials. Therefore; limiting the rate of force application as a function of displacement is evidenced by the loading Slope 1 being larger during dynamic bending (Figure 4.6a). Slope 1 during unloading (Figure 4.6c) is consistently smaller for the dynamic compared with the quasi-static loading methodology. Functionally, this means that the force is decreasing faster in the dynamic method. Slope 2 (second portion of load-deformation curve) appears more consistent across bending methods for both the loading (Figure 4.6b) and unloading (Figure 4.6d) phases. Essentially equal relationships with a line of best fit of gradient 0.99±0.02 for loading and 1.01±0.03 for unloading implies that for the second section of the load deformation curves, the rate of deformation across change in load is similar for both bending methods.

Force and displacement positions of the corner point for loading and unloading using both bending methods, providing an indication of the forces applied, are presented in
Figure 4.6. Comparison of bilinear Slopes for all poles for loading and unloading using both quasi-static and dynamic bending methods. The red line depicts a slope of 1 (equality between the two methods) and the black is a line of best fit to the data. Standard deviation are also shown for each pole.
Table 4.3: The behaviour of the pole from loading to unloading, with respect to energy has not been previously reported. In all cases the corner point is at greater displacement and the absolute force lower in the unloading bend compared with the loading.

The positions of the dynamic loading corner points appear to be consistently at smaller displacements than for quasi-static. Therefore; greater force is required to produce the initial bending of the pole because Slope 1 is greater for the slow dynamic curves. The slow dynamic unloading corner point does not appear to show any consistent position across the tested poles. However, the displacement at which this corner point is positioned is always greater than for all other curves. This is a representation of the slow dynamic unloading curve returning to small loads at greater deformation. While there is greater error involved in the dynamic data (especially in the unloading curves) it can be concluded that the intersection between the two slopes in the unloading curve occurs earlier in the dynamic method compared with the quasi-static. This will impact the amount of energy returned from the pole as it will be lower in a dynamic trial compared with quasi-static.

Table 4.3. Corner point force (newtons) and displacement (x in cm) for the Loading and Unloading of each pole for both quasi-static (QS) and dynamic bending methods.

<table>
<thead>
<tr>
<th>Pole #</th>
<th>QS Load</th>
<th>QS Unload</th>
<th>Dynamic Load</th>
<th>Dynamic Unload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (N)</td>
<td>X (m)</td>
<td>Force (N)</td>
<td>X (m)</td>
</tr>
<tr>
<td>2</td>
<td>500.80</td>
<td>0.9</td>
<td>471.28</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>533.71</td>
<td>0.6</td>
<td>505.52</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>724.35</td>
<td>0.8</td>
<td>689.29</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>708.30</td>
<td>1.2</td>
<td>671.67</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>610.12</td>
<td>1.1</td>
<td>577.11</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>616.35</td>
<td>0.9</td>
<td>585.21</td>
<td>1.1</td>
</tr>
<tr>
<td>9</td>
<td>602.31</td>
<td>0.7</td>
<td>564.48</td>
<td>0.9</td>
</tr>
<tr>
<td>10</td>
<td>557.12</td>
<td>0.6</td>
<td>527.82</td>
<td>1.1</td>
</tr>
<tr>
<td>11</td>
<td>541.00</td>
<td>1.0</td>
<td>513.01</td>
<td>1.5</td>
</tr>
<tr>
<td>12</td>
<td>515.78</td>
<td>0.8</td>
<td>486.60</td>
<td>1.7</td>
</tr>
<tr>
<td>13</td>
<td>792.08</td>
<td>0.8</td>
<td>745.58</td>
<td>1.3</td>
</tr>
<tr>
<td>14</td>
<td>853.33</td>
<td>1.1</td>
<td>811.98</td>
<td>1.8</td>
</tr>
<tr>
<td>15</td>
<td>629.48</td>
<td>1.0</td>
<td>592.68</td>
<td>1.4</td>
</tr>
<tr>
<td>16</td>
<td>587.82</td>
<td>0.6</td>
<td>554.64</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The corner points for the quasi-static method are more similar between loading and unloading and all occur at small displacement values. As with the dynamic curves, the unloading corner point for the quasi-static method is at a greater displacement than the
loading curve. This reinforces the dynamic testing results that indicate less energy is returned from the pole than is added during the loading phase; however this ratio disparity is not as large when applying the quasi-static method. This follows the same argument for the corner points as with the initial Slope 1; there is a time constant in the system with a delay between applying the force and the system coming to equilibrium during the quasi-static trials.

As mentioned above, at small displacements observable differences occur between the methods across the unloading curve. During the quasi-static trial, as the pole decompresses, the load-deformation curve diverges from the loading curve, then as it approaches the zero point it returns to match the loading curve. This result is not observed during dynamic testing where the unloading curve does not return to match the initial loading magnitudes. These quantified differences between the two loading curves have significance as it can be shown to explain a portion of energy lost during the vault. Further, the rest time between the force collection in the quasi-static method may help to explain this discrepancy. As the pole is unloaded dynamically the force decreases at a faster rate. However, if quasi-statically unloaded, the force increases to stabilise the pole at that displacement level. Despite the quasi-static method of pole bending being more simplistic and feasibly for data collection and analysis, the dynamic bending methodology offers benefits in better characterising energy aspects during a dynamic vault.

Figure 4.4 also highlights observable differences between the loading and unloading phases across the quasi-static and dynamic testing methods. This is most obvious for the higher displacement area of the bend. The difference can be explained through the phenomenon of hysteresis where the unloading curve does not follow the loading curve exactly. Hysteresis in the pole as shown in the graphs is a form of energy loss and has not previously been included in complete pole vault mechanical analyses. By quantifying the energy lost between the loading and unloading pole bending trials, this determined loss can be incorporated into any energy algorithm involving that specific model pole. Such an approach allows the resultant analysis to be more reflective of the energy added by the vaulter over the course of the entire vault and the subsequent outputs a more accurate and specific representation of pole-vaulter interaction.
Previous research investigating has assumed that pole behaviour across jumps is consistent with no attempt to incorporate manufacturing materials or bending characteristic differences between poles. Arampatzis et al. (2004) reported that an energy loss of 6-10% occurred during the transfer of energy through the pole during a vault with Schade et al. (2006) reporting a figure of 7%. These energy losses were explained by friction in the plant box and viscoelastic properties of the poles without demonstrating how this figure was determined. The equations developed in this investigation allow for the direct calculation of the energy stored in an individual pole and also the quantification of lost energy lost through the unloading phase.

The energy equation (Equation 3) enables the calculation of the energy stored and regained from a bending trial for each pole and subsequent lost energy through the bend (area between loading and unloading curves), with resultant values displayed in Table 4.4 and 4.5. The calculated percentage of energy lost during the bending phase is also presented.

Table 4.4. The maximum force applied, calculated energy stored, returned, lost and the percentage energy loss for all poles using the quasi-static bending method.

<table>
<thead>
<tr>
<th>Pole #</th>
<th>Manufacturer</th>
<th>Flex Rating (cm)</th>
<th>Max Force (N)</th>
<th>Max Energy (J)</th>
<th>Energy Return (J)</th>
<th>Energy Loss (J)</th>
<th>Loss %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>A</td>
<td>21.5</td>
<td>615.2</td>
<td>780.5</td>
<td>751.0</td>
<td>29.5</td>
<td>3.78</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>20.9</td>
<td>643.2</td>
<td>788.0</td>
<td>759.5</td>
<td>28.5</td>
<td>3.62</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>17.0</td>
<td>872.9</td>
<td>1213.8</td>
<td>1163.5</td>
<td>50.3</td>
<td>4.14</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>17.5</td>
<td>846.9</td>
<td>1158.0</td>
<td>1106.3</td>
<td>51.6</td>
<td>4.46</td>
</tr>
<tr>
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<td>22.1</td>
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<td>1025.3</td>
<td>984.9</td>
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<td>3.94</td>
</tr>
<tr>
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<td>A</td>
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<td>1016.4</td>
<td>984.9</td>
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<td>32.7</td>
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<tr>
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<td>31.8</td>
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<td>737.1</td>
<td>711.1</td>
<td>26.0</td>
<td>3.52</td>
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</table>
Table 4.5. The maximum force applied, calculated energy stored, returned, lost and the percentage energy loss for all poles using the dynamic bending method.

<table>
<thead>
<tr>
<th>Pole #</th>
<th>Manufacturer</th>
<th>Flex Rating (cm)</th>
<th>Max Force (N)</th>
<th>Max Energy (J)</th>
<th>Energy Return (J)</th>
<th>Energy Loss (J)</th>
<th>Loss %</th>
</tr>
</thead>
<tbody>
<tr>
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<td>21.5</td>
<td>636.1</td>
<td>812.0</td>
<td>762.5</td>
<td>49.5</td>
<td>6.10</td>
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<td>20.9</td>
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<td>76.7</td>
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<td>A</td>
<td>17.5</td>
<td>846.2</td>
<td>1145.6</td>
<td>1072.1</td>
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<td>69.1</td>
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<td>5.59</td>
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<tr>
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<td>9.77</td>
</tr>
</tbody>
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The results of the different quasi-static and dynamic bending regimes employed show observable differences for the pole energy variables. To test the significance of these differences paired sample t-tests were conducted for each calculated energy variable. All energy calculations were significantly different when comparing the quasi-static [Q] with the slow dynamic [D]; max energy (Q 946.4J v D 958.7J; \( p=0.04 \)), energy return (Q 910.3J v D 884.0J; \( p<0.001 \)), energy loss (Q 36.2J v D 74.7J; \( p<0.001 \)) and percentage energy lost (Q 3.84 v D 7.89; \( p<0.001 \)). The most notable difference is in the calculated energy lost; with the quasi-static (36.2 J) displaying on average smaller and more consistent energy losses across poles compared with the dynamic (74.7 J) method, due to greater hysteresis. This is not a simple relationship between the force applied and the deformation of the pole and there was potentially more error involved in the dynamic measurement process due to the complicated nature of this procedure; specifically the initial period of bend where the load applied increases dramatically for minimal displacement. This difference has significance to the pole vaulting action as it can be shown to explain a portion of energy lost. The previously mentioned settling (rest) time between each force collection epoch in the quasi-static method helps to explain this discrepancy in some cases.

Initial testing provided an indication that recorded dynamic forces may be greater than quasi-static. Table 4.4 and 4.5 indicate this to be true for the majority of poles however
to a lesser extent for poles five, six and nine, and the opposite found for pole ten (maximum dynamic forces were smaller). This remains to be explained and further and more careful measurement is recommended.

There is strong evidence that pole vault poles behave very differently when the method of loading is manipulated. Modelling a pole’s bend is a difficult proposition as they are not constructed of uniform thickness, diameter, stiffness or length and can also, depending on their manufacturer, be made from different materials. Previous authors have conducted pole modelling with the goal of explaining how a pole is bent during a vault (Griner, 1984), the best timing of pole bending (Fukushima et al., 2013), optimal pole construction (Burgess, 1998; Jahromi et al., 2012), or the influence of a pole’s characteristics (Ekevad & Lundberg, 1997; Jahromi et al., 2012; Morlier, Mesnard, & Cid, 2008). These investigations have provided essential data to the behaviour of a pole during a vault. However, these methodological processes are difficult to integrate into a pole vault biomechanical analysis to aid performance analysis.

Given the dynamic nature of the pole vault event, the observed relationship between energy loss in the slow dynamic and quasi-static bending regimes highlights the importance of accounting for energy loss during the pole recoil phase of pole vaulting. This energy loss will be a contributing factor in the outcome of the vault and must be acknowledged and accounted for in energy calculations. The integration of the force equation (Equation 2) to produce the energy function (Equation 3) for a pole facilitates the incorporation of pole-specific energy characteristics derived from the coefficients identified during a dynamic testing trial into any vault analysis using that same pole. Pole specific energy calculation has not been presented previously in the literature and given the known importance of the pole stiffness in vaulting (Jahromi et al., 2012) could potentially account for a significant component of overall performance.

4.4 SUMMARY AND CONCLUSIONS
4.4.1 Review of Hypotheses
Specific pole vault pole characteristics were investigated across a variety of pole vault poles that were used in comprehensive pole vaulting analyses to follow. This testing was conducted using a variety of methodologies for examining the load-deformation parameters during both loading and unloading phases of pole bend. As hypothesised, poles displayed non-uniform bend as depicted by low $R^2$ values across all bending
regimes. In addition to standard manufacturer static testing regimes, two complex individual pole characterisation methods (quasi-static and slow dynamic) were developed and investigated. The slow dynamic bending regime exhibited higher values for energy storage capacity with clear differences observed between the two bending methods for all poles, especially for the calculated energy lost. These results provide an indication of the important contribution of the pole to overall vaulting performance and allow a more accurate and pole specific analyses to be undertaken in order to assist with effective biomechanical analyses.

4.4.2 Conclusions

This novel study has clearly shown that the load deformation relationship of a pole vault pole is complicated. Characterising a pole with a single number from a static load test, as commonly undertaken by commercial pole manufacturers, does not provide a comprehensive description of the bending characteristics of a pole, especially with regard to its behaviour during an actual vault. This study revealed a new approach for characterising poles using a bilinear fit to the load deformation curve, thereby provides a more detailed description of pole bending behaviour that should be considered.

An empirical fitting function was developed providing specific coefficients to individual poles to reproduce the load deformation curve which can be utilised in future pole vault analyses when calculating stored, recovered and lost energy during a vault. The quasi-static method for assessing pole bending is simpler in regards to data collection and analysis. However, to increase the ecological validity and reproducibility of pole characteristics, the dynamic load deformation trials are a crucial addendum to the developed testing methodology. The data in this study gives a clear indication that there exists a time delay in the pole response to the force applied within the quasi-static testing methodology. This effect is clearly displayed when the quasi-static method is compared with the slow dynamic method results. The relevance here is clear given pole vaulting is a highly dynamic event where the pole rapidly bends and recoils. There is scope to improve the accuracy of the dynamic measures and therefore provide greater reproducibility in the dynamically derived pole measurement data. While increased errors were identified during dynamic testing it remains evident that the poles behaved differently under the two testing regimes. Measuring dynamic pole deformation during vaulting performance is important and is an area that needs further investigation. With the empirical function developed in this investigation the energy stored, lost and
regained from the pole can be calculating during a subject specific pole vault analysis in Chapter 5.
Energetic measures as performance indicators:

Do body specific inertial parameters effect energy calculations in male and female pole vaulters
5.1 INTRODUCTION
Performance in pole vaulting is ultimately determined by how high the vaulter can
displace their total body centre of mass (COM). This outcome is heavily reliant on
efficient transfer of energy throughout the vaulting phase. The initial kinetic energy
(KE) from the approach is transferred into the pole as elastic potential energy (EPE)
from the time of pole plant through to maximum pole bend. This EPE is then regained
by the vaulter as gravitational potential energy (GPE) as the pole recoils and propels the
vaulter vertically, while still maintaining horizontal motion, to clear the bar. The
efficiency of a vaulter at transferring energy into the pole and then maximising energy
in the later phases of the vault is crucial to the peak height achieved. An important
component in the derived energy calculations are the body segment inertial parameter
(BSIP) information generally calculated via indirect estimation.

With improving technology and in an effort to gain a better understanding of BSIPs
among different populations, researchers have looked beyond the traditional regression
tables commonly employed for this purpose and preferentially turned to the calculation
of subject specific measures. Indirect estimation methods which generally involve
regression equations developed from empirical data collected from human cadaver
specimens (Chandler et al., 1975; Dempster, 1955; Yeadon, 1990) or from imaging
techniques. Indirect measurement of BSIPs is widely and preferentially used as it
involves the direct reading of existing anthropometric BSIP information tables.
However, a major limitation using the indirect approach is that the original empirical
data used in the development of the regression equation may not be representative of the
target population (Durkin & Dowling, 2003). The direct approach involves calculating
subject specific BSIP directly from the participant via imaging techniques such as such
as dual-energy X-ray absorptiometry (DXA). Direct methods are therefore more
accurate and robust than standard regression tables and certainly more relevant for
populations found bookending the average normative scale (e.g. elite athletes). Such
individualised measures have been previously reported for swimming athletes (Rossi et
al., 2013), where significant differences between the elite swimming sample and
normative population derived in BSIP masses and locations were observed. This
research suggests that when kinetically modelling specific populations (especially
within elite sports), subject specific inputs may be required for improved validity (Rossi
et al., 2013). Studies have also reported that body morphologies of elite athletes are
often optimised for their desired sport, away from normative band thresholds. (Olds &
Subsequently, direct methods of BSIP calculation may be more appropriate for populations that sit at either end of the normative band, such as elite pole vault athletes, who likely present with somatotypes not reflected in general population averaged datasets.

It is possible that small differences in BSIP may affect the resulting energy calculation that relies on BSIP input data. The downstream effect of BSIP mass and location variance on energy calculations has not previously been documented. With previous studies relying on typically developing male Caucasian populations and cadaver data, there is the potential for large differences in the BSIP of normative datasets to that of elite male and female pole vault athletes.

The role of energy in the pole vault has been previously reported in the literature (Arampatzis et al., 2004; Schade et al., 2004; Linthorne, 2000; Tidow, 1989) though with little focus on energy flow through each phase (approach, take-off, support and flight) of the vault, or how individual energy components (translational KE, rotational KE and GPE) correlate with performance. These investigations have been typically limited to analysis of the absolute energy values at discrete phases of the vault. How the energy flow into and out of the specific poles and how it relates to the resultant vaulter COM energy has not been investigated. Current literature within the area focusing on optimisation and identification of critical variables effecting performance is sparse.

The aim of this study was to investigate the variation of the direct subject specific BSIP estimation method against five indirect methods for pole vault athletes and to determine the effect that direct and indirect methods could have on the calculation of rotational KE and total vaulter energy through the vault. Utilising subject specific direct methods for BSIP energy components and flow through the vault were investigated with a comparison between males and females, then to determine significant variables correlated to performance.

It was hypothesised that there would be no significant differences between the body segment estimation methods for segment mass and COM location. Also, the resultant energy calculations would not present significant differences through the vault. It was further hypothesised that identifiable differences would be displayed between males and
females with males displaying greater mass-normalised energy at initial, maximum pole bend (MPB), pole straight and peak height time points, as well as for calculated values of energy decrease, increase and gain. Males would also present significantly greater in the waveform comparisons of energy components. Finally, the initial KE and the overall energy through the vault would the positively correlated to peak height.

5.2 METHODS

5.2.1 Participants
A total of eight pole vault athletes, four male pole vault athletes (age 25.7 ± 6.2 years, height 187.8 ± 4.7 cm, mass 83.6 ± 5.4 kg) and four female (age 21.1 ±5.9 years, height 170.5 ± 4.7 cm, mass 59.6 ± 2.9 kg) who were national level or higher (including world championship and Olympic Games titles or experience) participated in the study. Approval was obtained from the Australian Institute of Sport Ethics Committee (20110401) and The University of Western Australia Human Research Ethics Committee (RA/4/1/5172) (Appendix A). All participants were provided with study information sheets and provided written informed consent prior to study participation.

5.2.2 Procedures
The procedures for the calculation of BSIP data and recording of pole vault trials are outlined in detail in Chapters 3.3 and 3.4. All participants underwent a DXA scan and a 3D body surface scan to facilitate subject the calculations of segment mass and COM location. A total of 67 vaults were recorded from the eight athletes. Data was collected over multiple testing sessions; with uneven trial numbers collected from each athlete due to training requirements and athlete management (a full list of the jumps recorded is presented in Appendix C). Six camera recordings at 25 Hz were optimally positioned around the vaulter and pole GRF, sampled at 500 Hz was recorded (further information is outline in the Chapter 3.5). Video and GRF data were synchronised post-hoc by an LED light positioned in the field of view that matched with the GRF recording. Testing sessions were conducted within normal training sessions that were directed by coaches and the athletes were provided with no instructions from the research team. Any information that could possibly preclude the jump was recorded along with descriptive variables for each jump (bar height, stand position and pole details such as length, flex and grip height).
5.2.3 Data Treatment

Body segment data was calculated in accordance with the methods outlined in Rossi et al. (2013) and are explained in further detail in Chapter 3.4. For the single direct method, the DXA scan was segmented and the individual segment properties calculated in Matlab® (Ver. 7.8.0.347). The anthropometric data obtained from the 3D surface scans were used for estimating segment properties using the five indirect methods; the Modified Chandler method (C) (Chandler et al., 1975), the Modified Yeadon method (Y) (Yeadon, 1990), the Zatsiorsky Simple Regression method (Z1) (Zatsiorsky and Seluyanov, 1983), the Zatsiorsky Multiple Regression method (Z2) (Zatsiorsky and Seluyanov, 1985) and the Zatsiorsky Geometric Model (Z3) (Zatsiorsky, Seluyanov and Chugunova, 1990).

Calculation of the energy parameters was conducted using a custom computer program written in IGOR Pro (WaveMetrics IGOR Pro 6) software (a simplified version of the programming is presented in Appendix D). The energy of the vaulter was calculated using the following equations.

The total KE for the motion of the vaulter's body during the vault was analysed by separating the translational KE of the COM of the whole body and the rotational KE of the segments about the COM. The COM of the whole body is calculated using the masses for each segment and the marker positions from the 3D digitisation. These depend on the body segment model being used. The translational KE for each frame is then calculated using the mass of the whole body ($m_{\text{whole}}$) and its velocity ($v_c$).

\[
\text{Translational KE} = \frac{1}{2} m_{\text{whole}} v_c^2
\]

Once the inferred position of the centre of mass of a segment is determined, the rotational KE is calculated by treating the segment as a point mass at that position. The rotational kinetic energy for each segment was calculated from the digitised dynamic data using the inferred positions of the centre of mass of the segment and its radial distance and rotation relative to the centre of mass for the whole body.

\[
\text{Rotational KE (segment i)} = \frac{1}{2} I_i \omega_i^2 = \frac{1}{2} m_i v_i^2
\]

where $v_i$ is the velocity of the segment centre of mass with respect to the whole body centre of mass. The effective moment of inertia ($I_i$) and angular velocity ($\omega_i$) are
\[ I_i = m_i R_i^2 \quad \text{and} \quad \omega_i = \frac{v_i}{R_i} \]

where \( R_i \) is the relative distance of the inferred segment centre of mass from the whole body centre of mass. The GPE of a vaulter of total mass (\( m_{\text{whole}} \)) is calculated from the height of the vaulter's centre of mass (h) according to:

\[ \text{GPE} = m_{\text{whole}} g h \]

where \( g \) is the acceleration due to gravity (\( g = 9.80 \text{ m s}^{-2} \)).

The total energy of the vaulter (\( E_{\text{tot}} \)) is then the sum

\[ E_{\text{tot}} = \text{GPE} + \text{Translational KE} + \text{Rotational KE} \]

The elastic energy stored in the pole (EPE) under compression was determined using the parametrisation of the load-deformation response for each pole (Chapter 4). The total energy of the system (TE) for each frame is then the sum

\[ \text{TE} = \text{GPE} + \text{Translational KE} + \text{Rotational KE} + \text{EPE} \]

Continuous waveform data was calculated for all energy components and normalised by vaulter mass and across time. Discrete energy data was extracted at specific time points throughout the vaulting phase including the mid-point of the last stride (Initial), maximum pole bend (MPB), pole straight (PS) and peak COM height (PH). These temporal points allowed the vaulting manoeuvre to be examined by distinct commonly used vaulting phases bordered by the temporal points.

To assess variability of mean data across the vaulting phases a coefficient of variation (CV) was calculated by dividing the standard deviation by the mean for each vault and then averaged over males and females. This was conducted for the rotational KE and total vaulter energy curves across each vault and a mean CV (per variable) determined for each vaulter. Statistical analyses were undertaken using IBM® SPSS® Statistics 21 (IBM Corporation, Armonk, NY, USA). A one-way ANOVA was performed to assess for differences in segment mass across 6 segments, COM location and to identify initial significant between the CV results. A Tukey-HSD post-hoc analysis was used to determine differences between the estimation methods. Independent samples t-tests were used for differences between male and female pole vaulters for the selected variables with the significance level of \( \alpha<0.05 \). Finally, a multiple linear regression analysis was conducted to determine predictors of peak height.
The open source one dimensional statistical parametric mapping (SPM) package (SPM1D (33)) was used to statistically compare continuous waveform data using Matlab® (Ver. 7.8.0.347). The SPM was computed at each point in the normalised time series for each energy component and total energy data sets, forming a statistical parametric map (Pataky, 2010; Robinson et al., 2014). This methodology has been used previously in comparison of knee joint kinematics to determine the influence of direct and inverse kinematic modelling (Robinson et al., 2014). Unlike traditional statistical analyses methods that assess for differences between single value discrete time points, this statistical methodology provides a method for comparing two continuous data series (e.g. joint angles across stance) and identifies areas of waveform data that are significantly different. The statistical significance value for SMP analysis was also set to $\alpha<0.05$.

5.3 RESULTS AND DISCUSSION

5.3.1 Body segment inertial parameters

The means and standard deviation (SD) for segment mass and COM location of the four males and four female vaulters were calculated using five indirect methods and the direct DXA method. The results of these comparisons are displayed in Tables 5.1 and 5.2. Statistical differences were found between the DXA method and the five indirect methods across a number of variables.

No significant differences in head segment mass determination were observed between the DXA and the indirect methods in both males and females. No differences were also found for the male forearm, thigh and shank segments. To calculate the percentage difference from the DXA method, the DXA value was subtracted off the indirect value and the difference divided by the DXA value. Compared with the DXA method, male trunk mass was overestimated when using the Chandler (18%, $p<0.01$) and Z2 (16%, $p<0.01$) methods. Females also recorded significantly overestimated trunk mass with the Chandler (21%, $p<0.01$), Yeadon (16%, $p=0.03$) and Z2 (18%, $p=0.01$) methods. Male upper arm mass was underestimated by all indirect models when compared with the subject specific DXA output; Chandler (24%, $p<0.01$), Yeadon (18%, $p<0.01$), Z1 (26%, $p<0.01$), Z2 (14%, $p<0.01$) and Z3 (33%, $p<0.01$). The upper arm was also significantly underestimated for females using the Z3 method (33%, $p<0.01$). The Z1 method also significantly overestimated forearm (29%, $p<0.01$) and thigh (15%, $p<0.01$) mass compared with DXA outputs in the female sample. Finally, female shank
mass was underestimated using the Chandler method by approximately 12% (p=0.02) yet overestimated using the Yeadon method by 20% (p<0.01).

Comparisons of the DXA method to the five indirect methods also uncovered differences in the COM location determination across segments. All locations are in relation to the proximal end point with the trunk location from the midline of the hips. Trunk location in male pole vaulters was significantly overestimated compared with the DXA method using Chandler’s method (14%, p<0.01) though underestimated when all other indirect methods were applied; Yeadon (16%, p<0.01), Z1 (17%, p<0.01), Z3 (15%, p<0.01) and Z2 (9%, p<0.01). Trunk COM location for females was overestimated with the Chandler method by 16% (p<0.01) although underestimated with Z1 (19%, p<0.01) and Z2 (12%, p<0.01). Males presented with significantly overestimated upper arm locations with all indirect methods except Z3; Chandler (23%, p<0.01), Yeadon (14%, p<0.01), Z1 (17%, p<0.01), Z2 (10%, p<0.01). The upper arm in females also showed overestimated locations with Chandler (23%, p=0.03) and Z2 (10%, p<0.01). Male forearm COM location was overestimated with Z1 (7%, p<0.01). The forearm location for females was found to be underestimated with Yeadon (8%, p<0.01) while significantly overestimated using Z3 (14%, p<0.01). Male and female thigh locations were overestimated with Z1 (7%, p<0.01 and 12%, p<0.01, respectively) and Z2 (16%, p=0.04 and 18%, p<0.01, respectively). Shank COM location in males using the Yeadon method was overestimated (12%, p=0.02). Female shank COM location was overestimated with Z3 (9%, p<0.01) and slightly, though significantly underestimated, with Yeadon (10%, p<0.01) and Z2 (8%, p<0.01).

Calculating subject specific body segment data using direct methods showed significant variation compared with commonly employed indirect methods. Rossi et al. (2013) concluded, when investigating elite male and female swimmers, that indirect estimation methods should be avoided when applied to a population that is of different morphology and body composition to that which the indirect estimation method is derived. When investigating an athlete population such as elite pole vaulters, it is likely that their body morphology is not reflective of the general population and it may be more appropriate to employ subject specific BSIP collection methodologies (Durkin & Dowling, 2003, Olds & Tomkinson, 2009). No specific published information could be found concerning specific anthropometric data of elite pole vaulters. Anecdotally however, the pole vaulter’s body form typically tends towards an ectomorphic body shape with
definite mesomorphic tendencies in the upper arms and upper trunk as required to provide the strength and power to handle the impact loading at pole plant and perform the subsequent vaulting manoeuvres.

It may be assumed that because the large proportion of the body mass is in the trunk segment, any differences to the mass and location for this section will have greater effect on calculations derived using this information. Trunk values did demonstrate significant observed differences between the DXA and indirect methods (specifically Chandler, Yeadon and Z2). This finding reinforces the view that subject specific methods may provide more relevant results to the target population. It has previously been reported that the Chandler method also performed poorly when used for calculation of COM for swimmers, especially for the trunk segment (Rossi et al., 2013). Despite the low number of subjects in this investigation, the differences observed provide a clear indication that using subject specific direct methods should be preferred over indirect BSIP estimation methodologies.

5.3.2 Effect of varying segment models on energy calculations

The five indirect methods of calculating BSIP all showed partial differences for segment mass and COM position compared with the direct DXA method. Within the five indirect methods, the Chandler method demonstrated the greatest variation from the ground truth subject specific data (DXA data). The influence of variation of BSIP calculations on dynamic analyses of elite athletes, who present with expected differences in body physique, was also assessed. This was performed by specifically focussing on the resultant effect of the BSIP calculation methods on both the rotational KE curves and total body energy curves calculated during dynamic vaulting (real) trials. All vaults were time normalised from initial energy to peak height; with energy also normalised to body mass.

As discussed previously, the total body energy is calculated from three different energy components; translational KE, rotational KE and the GPE. Of these three components, the translational KE and gravitational potential energy is calculated using equations that require segment COM information. The rotational KE involves the rotational components of each individual body segment about the total body COM; and may be influenced to a greater degree by variations in the BSIP resulting from the application of different BSIP methodologies.
Table 5.1. Mean (SD) segment body mass percentage for male (4) and female (4) pole vaulters using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model.

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<th>Segment</th>
<th>Gender</th>
<th>DXA</th>
<th>C</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Male</td>
<td>5.92 (0.28)</td>
<td>5.50 (0.18)</td>
<td>5.92 (0.57)</td>
<td>6.51 (0.29)</td>
<td>6.99 (1.00)</td>
<td>6.10 (0.50)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>7.31 (0.28)</td>
<td>6.46 (0.09)</td>
<td>6.82 (0.69)</td>
<td>8.08 (0.19)</td>
<td>7.56 (1.00)</td>
<td>7.16 (0.71)</td>
</tr>
<tr>
<td>Trunk</td>
<td>Male</td>
<td>44.49 (1.09)</td>
<td>52.35 (0.07)**</td>
<td>44.04 (2.28)</td>
<td>43.12 (0.16)</td>
<td>51.61 (5.21)**</td>
<td>46.92 (1.18)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>43.06 (0.28)</td>
<td>51.99 (0.03)**</td>
<td>49.87 (3.45)*</td>
<td>42.21 (0.67)</td>
<td>50.88 (5.87)**</td>
<td>44.31 (1.65)</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>Male</td>
<td>3.54 (0.13)</td>
<td>2.68 (0.06)**</td>
<td>2.90 (0.18)**</td>
<td>2.63 (0.17)**</td>
<td>3.04 (0.10)**</td>
<td>2.36 (0.07)**</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>3.10 (0.20)</td>
<td>3.01 (0.03)</td>
<td>3.05 (0.37)</td>
<td>3.05 (0.04)</td>
<td>2.94 (0.09)</td>
<td>2.09 (0.16)**</td>
</tr>
<tr>
<td>Forearm</td>
<td>Male</td>
<td>1.78 (0.15)</td>
<td>1.67 (0.00)</td>
<td>1.64 (0.26)</td>
<td>1.53 (0.09)</td>
<td>1.68 (0.18)</td>
<td>1.63 (0.04)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>1.43 (0.17)</td>
<td>1.67 (0.00)</td>
<td>1.54 (0.13)</td>
<td>1.85 (0.02)**</td>
<td>1.63 (0.13)</td>
<td>1.37 (0.19)</td>
</tr>
<tr>
<td>Thigh</td>
<td>Male</td>
<td>13.15 (0.30)</td>
<td>12.76 (0.01)</td>
<td>11.83 (1.48)</td>
<td>13.98 (0.94)</td>
<td>13.50 (0.62)</td>
<td>13.48 (0.26)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>14.03 (0.37)</td>
<td>12.80 (0.00)</td>
<td>14.71 (0.52)</td>
<td>16.16 (0.34)**</td>
<td>13.39 (1.62)</td>
<td>15.02 (0.47)</td>
</tr>
<tr>
<td>Shank</td>
<td>Male</td>
<td>4.62 (0.18)</td>
<td>4.19 (0.02)</td>
<td>4.76 (0.50)</td>
<td>4.24 (0.28)</td>
<td>4.70 (0.23)</td>
<td>4.40 (0.36)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>4.65 (0.30)</td>
<td>4.10 (0.01)*</td>
<td>5.60 (0.27)**</td>
<td>4.99 (0.14)</td>
<td>4.86 (0.24)</td>
<td>4.31 (0.22)</td>
</tr>
</tbody>
</table>

* Significantly different to DXA method (p<0.05)
** Significantly different to DXA method (p<0.01)
Table 5.2. Mean (SD) percentage of the segment length for segment centre of mass position from proximal end point for male (4) and female (4) pole vaulters using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Gender</th>
<th>DXA</th>
<th>C</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Trunk</td>
<td>Male</td>
<td>53.58 (1.42)</td>
<td>61.19 (0.00)**</td>
<td>45.05 (1.68)**</td>
<td>44.27 (2.31)**</td>
<td>45.38 (2.17)**</td>
<td>48.62 (0.00)**</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>52.86 (0.44)</td>
<td>61.19 (0.00)**</td>
<td>48.84 (3.07)</td>
<td>42.72 (3.45)**</td>
<td>46.46 (2.30)**</td>
<td>48.62 (0.00)</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>Male</td>
<td>41.22 (1.10)</td>
<td>50.58 (0.00)**</td>
<td>46.83 (3.38)**</td>
<td>48.07 (2.14)**</td>
<td>45.28 (0.53)**</td>
<td>42.28 (0.00)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
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<td>50.58 (0.00)*</td>
<td>38.73 (8.55)</td>
<td>46.92 (4.05)</td>
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<td>42.28 (0.00)</td>
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<tr>
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<td>43.93 (1.70)**</td>
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<td></td>
<td>Female</td>
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<td>41.59 (0.00)</td>
<td>36.68 (1.18)**</td>
<td>40.42 (2.09)</td>
<td>39.95 (0.28)</td>
<td>45.74 (0.00)**</td>
</tr>
<tr>
<td>Thigh</td>
<td>Male</td>
<td>40.85 (1.38)</td>
<td>39.49 (0.00)</td>
<td>45.86 (6.63)</td>
<td>48.19 (0.66)*</td>
<td>47.38 (0.35)**</td>
<td>40.95 (0.00)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>40.08 (1.02)</td>
<td>39.49 (0.00)</td>
<td>40.51 (1.48)</td>
<td>45.02 (1.67)**</td>
<td>47.33 (0.39)**</td>
<td>40.95 (0.00)</td>
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<tr>
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<td>Female</td>
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<td>39.85 (1.32)</td>
<td>37.89 (0.19)**</td>
<td>44.59 (0.00)**</td>
</tr>
</tbody>
</table>

* Significantly different to DXA method (p<0.05)
** Significantly different to DXA method (p<0.01)
Table 5.3. Mean (SD) coefficient of variation of rotational kinetic energy and total vaulter energy for males (4) and females (4) calculated across all vaults using DXA and five indirect methodologies. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Gender</th>
<th>Estimation Method</th>
<th>DXA</th>
<th>C</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
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<tbody>
<tr>
<td>Rotational KE</td>
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<td>0.57 (0.04)</td>
<td>0.51 (0.05)</td>
<td>0.52 (0.04)</td>
<td>0.58 (0.04)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>0.48 (0.07)</td>
<td>0.62 (0.09)</td>
<td>0.57 (0.07)</td>
<td>0.52 (0.08)</td>
<td>0.53 (0.08)</td>
<td>0.58 (0.08)</td>
</tr>
<tr>
<td>Total Energy</td>
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<td></td>
<td>0.24 (0.00)</td>
<td>0.26 (0.00)**</td>
<td>0.25 (0.00)*</td>
<td>0.25 (0.00)</td>
<td>0.25 (0.00)</td>
<td>0.25 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>0.22 (0.02)</td>
<td>0.24 (0.03)</td>
<td>0.23 (0.03)</td>
<td>0.23 (0.02)</td>
<td>0.23 (0.03)</td>
<td>0.23 (0.02)</td>
</tr>
</tbody>
</table>

* Significantly different to DXA method ($p<0.05$)
** Significantly different to DXA method ($p<0.01$)
Table 5.4. Percentage differences for segment mass between the Indirect BSIP methods and the DXA. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model.

<table>
<thead>
<tr>
<th>Estimation Method</th>
<th>Segment</th>
<th>Gender</th>
<th>C</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>-6.78</td>
<td>0.34</td>
<td>10.34</td>
<td>18.47</td>
<td>3.39</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>-11.63</td>
<td>-6.70</td>
<td>10.53</td>
<td>3.42</td>
<td>-2.05</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>17.67</td>
<td>-1.01</td>
<td>-3.08</td>
<td>16.00</td>
<td>5.46</td>
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<tr>
<td></td>
<td>Female</td>
<td></td>
<td>20.74</td>
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<tr>
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<td>-1.61</td>
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<td>-8.43</td>
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<tr>
<td></td>
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<td>16.78</td>
<td>7.69</td>
<td>29.37</td>
<td>13.99</td>
<td>-4.20</td>
</tr>
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<td></td>
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<td>2.66</td>
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<td>4.85</td>
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<td></td>
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<td>3.03</td>
<td>-8.23</td>
<td>1.73</td>
<td>-4.76</td>
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<tr>
<td></td>
<td>Female</td>
<td></td>
<td>-11.83</td>
<td>20.43</td>
<td>7.31</td>
<td>4.52</td>
<td>-7.31</td>
</tr>
</tbody>
</table>

Table 5.5. Percentage differences for segment COM location between the Indirect BSIP methods and the DXA. (C) Chandler model; (Y) Yeadon model; (Z1) Zatsiorsky simple regression model; (Z2) Zatsiorsky multiple regression model; (Z3) Zatsiorsky geometric model.

<table>
<thead>
<tr>
<th>Estimation Method</th>
<th>Segment</th>
<th>Gender</th>
<th>C</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>15.76</td>
<td>-7.60</td>
<td>-19.18</td>
<td>-12.11</td>
<td>-8.02</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>22.71</td>
<td>13.61</td>
<td>16.62</td>
<td>9.85</td>
<td>2.57</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>23.37</td>
<td>-5.54</td>
<td>14.44</td>
<td>10.44</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>1.34</td>
<td>8.43</td>
<td>7.04</td>
<td>-2.63</td>
<td>11.45</td>
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<td></td>
<td>Female</td>
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<td>3.95</td>
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<td>1.02</td>
<td>-0.12</td>
<td>14.32</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>-3.33</td>
<td>12.26</td>
<td>9.69</td>
<td>15.99</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>-1.47</td>
<td>1.07</td>
<td>12.08</td>
<td>18.09</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td>-0.22</td>
<td>12.19</td>
<td>-6.03</td>
<td>-8.93</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td>0.68</td>
<td>-9.64</td>
<td>-2.95</td>
<td>-7.72</td>
<td>8.60</td>
</tr>
</tbody>
</table>

It has previously been documented that the rotational kinetic energy values are substantially lower than both the translational KE and GPE over the course of the vault and its influence is minimal (Schade et al., 2000; Arampatzis, 2004). Given potential theoretical variations in this energetic parameter, based on the BSIP method utilised, it was considered necessary to investigate whether these variations would reach significance. The average CV of all males and females for the rotational KE (Table 5.3) was compared between the DXA method and the five indirect methods. Results revealed that all indirect methods were not significantly different to the DXA method,
apart from males when using the Chandler method ($p<0.01$), which presented a significantly higher CV compared with the DXA results.

Total vaulter energy differences between the DXA and the five indirect estimation methods were also assessed using mean CV variables. Once again no significant differences between the DXA and the five indirect methods were found in the female cohort. However, it is important to note that the indirect estimation method regression equations are derived from a general population male sample; suggesting that the female pole vaulter body type is similar to the average male from which the indirect methods were initially derived from. Given there were little variability (evidenced by small SD) in the segment mass and location data when comparing the from the known DXA derived values to the indirect methods, it is likely that the female pole vaulter body type appears similar to the sample the indirect methods are derived. Conversely, the male pole vaulters, appear to be further removed from the anthropometric mass distribution of the general population used to establish the indirect BSIP regression tables. It is possible that the comparison of the female BSIP sample of this study, with indirect methodologies that include female specific BSIP (De Leva, 1996), may have resulted in greater variation in the female methodology comparisons. However, the purpose of this study was to examine regression tables commonly applied in applied sport biomechanics analysis and as such, clinically based regression tables that incorporate females specific data sets were not incorporated into this investigation. Further research involving female athletes should consider investigating the influence of deriving BSIP information using female specific regression tables. Finally, total vault energy calculated using the Chandler ($p<0.01$), Yeadon ($p=0.02$) and Z3 ($p=0.02$) indirect methods did exhibit significantly higher average CVs compared with the ground truth DXA values (Table 5.3).

Both rotational KE and total vaulter energy average CV values highlight that the highest variance in energetic data was observed when Chandler derived estimation methods were used to calculate the required BSIP inputs. To highlight the effect of this variation over the entire vault time series, an SPM analysis assessing energy variables (rotational and total vaulter) calculated using BSIP derived from ground truth DXA compared with Chandler’s indirect methodology, was conducted in male pole vaulters. This provided insight into which phases of the vault would be most affected by BSIP variation. SPM results are displayed in Figure 5.1. For the rotational KE, the significant difference
(p<0.001) occurs at the very beginning of the vault, correspond to the vaulter being in mid stride prior to final foot strike for take-off. It is also observed in the average rotational KE, that the standard deviation of the four male vaulters when using the DXA method is smaller than that of the Chandler method across the entire vault. An explanation for this is the specificity of the BSIP producing a more accurate value for input into the rotational KE equation.

Significant differences are also observed for the total vaulter energy at three distinct points throughout the vault. The initial difference is observed around the time of pole plant and shows the Chandler method producing significantly higher total energy values. The difference between the two curves is greater than the difference observed at the same time point in the rotational KE data. While this can be party associated with
the difference in rotational KE, there must also be another component of energy contributing to the remaining difference, such as internal joint kinetics of the vaulter.

SPM analysis then shows a second significant total energy difference, derived using the two BSIP estimation methodologies, at 60% to 80% of the vault. This generally corresponds to the period following maximum pole bend, as the vaulter is increasing GPE. Differences in the segment mass and its location affect the calculation of GPE and given that GPE is increasing dramatically during this time point it is unsurprising that variations in segment mass and COM location is affected by BSIP variations at this time (i.e. in periods where the rate of energy change will be high).

Wherever possible, when analysing subjects that are physically different to the sample base used to derive indirect method regression tables, direct BSIP calculation should be employed (Durkin & Dowling, 2003). These comparisons highlight the variation that can occur in the energy calculations in direct compared with indirect BSIP methods across a pole vault. The results reinforce the need for caution when choosing BSIP estimation methodology and specifically advises against adopting the modified Chandler method when analysing subjects (e.g. athletes) who present with body morphology that is likely to deviate from the normative band. Further, these results indicate that the BSIP differences identified when using the Z1 and Z2 methods are not significantly large enough to result in downstream changes to resultant energy calculations. Therefore, if direct measurement is not available and energy outputs are of interest, then these indirect regression methods are recommended.

### 5.3.3 Energy in the pole vault

The efficiency of energy production, storage and recovery by a vaulter throughout the vault is vital for effective pole vaulting. The overall principle of energy in the pole vault is not complex; maximise the initial energy input whilst minimising energy losses, while providing as much added energy during the vaulting phase as possible in order to create maximal GPE in order to clear the bar. Large energy losses occur at the plant and take off events (Linthorne, 2000), while work done by the vaulter on the pole can add energy to the vault. The storage of energy in the pole facilitates the vaulter transferring initial KE into GPE, however this EPE exchange with the pole must be effective for the vaulter to store and regain the required energy. If too much of the initial KE is lost (i.e.
not stored in the pole) then there will be less returned to the vaulter in later phases leading to decreased overall performance (COM height).

Figure 5.2. Mean and standard deviation of total energy, kinetic energy, gravitational potential energy and elastic potential energy for men (n=4) (top graph) and women (n=4) (bottom graph). Values are normalised to body mass. The x-axis is normalised to 100% at the initial point, 0% at maximum pole bend and 100% at the instant of peak centre of mass height.

The average mass normalised energy curves for males and females are presented in Figure 5.2, that includes the EPE in the pole calculated using the empirical fitting function developed in Chapter 4. For accuracy, all vaulter energy calculations used
subject specific DXA BSIP information. There are some qualitative observable differences between the male and female energy curves. However, the general patterns of the waveforms are similar; indicative of a similar technical model being employed by both cohorts. The initial decrease in KE into the plant is matched in the total energy, as the KE continues to decrease and the EPE stored in the pole is increasing, the total energy in the vaulter and the pole remains relatively consistent. During this time any energy that is being lost in the system is being matched by the input of added work by the vaulter. The KE continues to decrease through to maximum pole bend where the elastic potential energy is now at maximum and the GPE has gradually increased. As the pole begins to extend, the GPE increases dramatically and the total energy also increases. The vaulter continues to gain GPE after pole straight has occurred, as the energy gained through the vault can now be observed with the total energy at PH being greater than the initial energy. With the EPE calculated using the pole energy equation from study one, which is specific to the pole being used in each jump, the energy lost in the pole is accounted for in the final total energy calculation.

Biomechanical analysis of elite sporting populations can be challenging, especially with an individual sport such as pole vaulting due to often small participant pool available for testing. There are observable differences between the energy waveforms in this investigation, consistent with the previous analysis of Schade et al. (2004) who examined the last valid attempt by each vaulter in the Olympic Pole Vault Finals at the Sydney 2000 Olympic Games. The current study was more comprehensive in that multiple jumps were collected from each participant during training sessions and mean, arguably more representative data, has been presented.

Results of the total vaulter energy are presented in Figure 5.3. Statistically significant differences in the mass normalised energy data occurred between males and females at the initial time point, at pole straight where the pole has fully extended and at the point of peak height. These differences also occurred in the calculated energy increase from maximum pole bend through to peak height and the calculated overall gain in energy through the vault from initial to peak height events. Similar results were reported in male and female pole vaulters at the 2000 Sydney Olympics (Schade et al. 2004). Schade et al. (2004) presented differences at these time points and calculations of changes in energy except the total energy gained. This investigation produced no significant differences at MPB or for the decrease calculation (initial total vaulter
energy minus total vaulter energy at maximum pole bend) (although this was approaching significance, \( p=0.092 \)). There was a significant difference found between males and females for the calculated energy gain over the complete vault, where males were found to gain greater energy.

![Figure 5.3. Comparison of the total energy of the vaulter at discrete time points in the vault: Initial, Maximum Pole Bend, Pole Straight, and Peak Height as well as the calculated energy decrease, increase and total energy gained. * Significant difference (\( p<0.05 \)) between males and females.](image)

This analysis indicates that male vaulters displayed a higher initial energy, created from the approach that they effectively transferred into the pole. The higher energy increase for males compared with females can be explained by the males gaining greater benefit from the extending pole, and their ability to perform more active work on the pole in this phase.
Figure 5.4. Mass normalised male and female average and SD for energy calculations (translational KE, rotational KE, GPE, total vaulter energy and total overall energy) in the vaulting phase time normalised from initial to PH. SPM results displaying significant ($p<0.05$) differences on the left. 50% represents the temporal point MPB.

SPM analysis between the males and females was also conducted to determine where across the vault any major differences might be observed. All energy calculations were calculated using the subject specific direct body segment data and the EPE incorporated in the final graph is calculated using the pole specific coefficients from Chapter 4. Results of the SPM are displayed in Figure 5.4; the average energy curves for males and females of their translational KE, rotational KE, GPE, total vaulter energy and total overall energy, including EPE in the pole, are displayed in the graphs on the left. The respective SPM for each energy comparison is displayed on the right. The only significant difference found was that males displayed significantly greater gravitational potential energy in the relative time regions from 0-16% and 58-100% of the vault ($p=0.013$, and $p<0.001$, respectively). This may be due to the greater centre of mass height and strength males utilise resulting in higher take-off projection angles and greater drive that is not accounted for when normalising by body mass. It is therefore
unsurprising that males subsequently record increased heights in an inverted body position during pole extension, thereby increasing the GPE that can be achieved.

The average mass normalised energy curves for the males and females indicated that, despite some qualitative differences in magnitudes, the energy waveforms followed a similar pattern; indicative of a similar technical model being employed by both groups. These non-significant observable differences occurred for initial translational KE and were also identified across the entire phase for the total vault energy and the total overall energy. While the EPE incorporated into the overall total energy does not affect the significance of the SPM, it does appear to decrease the observed qualitative difference between males and females. This implies that, when mass normalised, the energy storage in the pole is greater for females.

5.3.4 Discrete energy variables correlated to peak height

Pole vaulting is an extremely complex event where performance ultimately boils down to the peak height achieved by the vaulter. No previous research has examined the efficacy of energetic variables as distinguishing determinates of overall performance. The potential identification of energetic variables that correlate with peak height may enhance the biomechanical feedback provided to athletes by way of strategies employed by pole vault coaches and athletes. Additionally, via incorporating increased individual specificity within the energy calculations, our aim was to determine if there were any distinguishing energetic variables that correlated with peak height.

A multiple regression analysis was conducted, for males and females separately, on specific variables that could theoretically contribute to the peak height reached. These variables included; the initial total energy of the vaulter, the energy of the vaulter at MPB, the EPE stored in the pole at MPB and the area under the total energy curve (Action). For males a significant model emerged, F(7,26) = 145.93, $p<0.001$. Approximately 97% of the variance in peak height was explained by the predictors (adjusted $R^2 = 0.97$). The model took into account the individual vaulter differences and this proved to be a significantly correlated variable ($p<0.001$). The total vaulter energy at MPB ($p=0.003$) and the Action ($p<0.001$) were also significant predictors. For females a similar significant model emerged to that displayed by males, F(7,39) = 91.47, $p<0.001$, where approximately 94% of the variance in peak height was explained by the predictors (adjusted $R^2 = 0.94$). The participant number again proved
to be a significantly correlated with peak height ($p<0.001$). The total vaulter energy at MPB ($p=0.024$) and the Action ($p<0.001$) were significant predictors once again. For both males and females the initial total energy and the EPE stored in the pole failed to make a significant contribution to peak COM height.

These results indicate that similar predictors of the peak height exist and that these are unaffected by gender influences. Accounting for the different vaulters in the model was necessary due to the uneven number of jumps for each vaulter, multiple poles being used and the fact that heights jumped across the eight athletes were variable. As expected, the results indicate that the level of vaulter is significant correlated to the overall height achieved. It was expected that the initial energy would be a significant factor influencing peak height; however this was not found to be the case. The initial energy is developed from the approach velocity and a possible explanation for this non-finding is that, when observing approach velocities within performance populations, the peak horizontal approach velocity does not differentiate between vault heights (McGinnis, 1986; Mueller & Hommel, 1997; Young & Yeadon, 1997). The Action variable is an indication of the overall energy throughout the vault, with its significant finding indicating that increased energy over the vault will lead to higher jump heights. The final significant variable, total vaulter energy at MPB, provides an indication of the need for a vaulter to maintain as much energy as possible through the vault. A lower energy at MPB indicates that the vaulter has lost too much energy through the plant and pole loading phases, leading to decreased overall height reached. To understand this, it is important to consider the efficiency of energy patterns in pole vaulting performance (Dillman & Nelson, 1968). Minimising energy losses and maintaining greater energy through the vault will lead to improved performance.

5.4 SUMMARY AND CONCLUSIONS
5.4.1 Review of Hypotheses
Differences in BSIP between a direct DXA calculation method and five indirect methods, and their effect on rotational KE and total vaulter energy, were investigated across eight male and female pole vault athletes. Significant differences were found for segment mass and COM location across various body segments between the DXA and the indirect methods. As hypothesised, the methodology employed did not significantly influence BSIP determination in female pole vaulters. Significant effects were observed in the male athletes, with the Chandler indirect method displaying the greatest variation.
to the ground truth DXA derived BSIP values. As hypothesised, compared with females, males exhibited significantly higher discrete energy variable values at initial, pole straight and peak height phase times, as well as for their energy increase and gain across the vaulting phase. However, contrary to our hypothesis these discrete difference findings did not translate to energy components differences when the overall continuous (waveform) data was assessed using statistical parametric mapping analysis. The only significant difference in the continuous data energy analysis was observed in the gravitational potential energy results. Finally, our hypothesis for variables predicting peak height was partially supported with the overall energy, termed ‘Action’ (area under the energy curve), being a significant predictor. Likewise, the energy of the vaulter at maximum pole bend was found to be a significant predictor of peak COM height, although this was not specifically hypothesised.

5.4.2 Conclusions

It has been shown that calculating subject specific BSIP for pole vaulters will result in significantly different values than indirect methods. These differences do translate downstream, whereby energy calculations using BSIP inputs are influenced during pole vaulting analysis. Wherever possible, when reporting on subjects that are physically different to the sample base in which indirect method regression tables are derived, direct BSIP calculation should be employed.

An improved understanding of the energy components and flow throughout the vault allows the biomechanist to have an increased level of understanding surrounding the complex mechanical interactions of this highly technical event. As expected, males displayed greater energy through the vaulting phase in discrete variables due to their ability to produce greater initial energy from the approach and also gain more back as GPE from the extending pole in the later phases of the vault. It was observed that males and females exhibit similar strategies for the vaulting manoeuvre as the waveform analysis displayed similar trends with minimal statistical differences. Performance based on the height achieved is the ultimate aim in pole vaulting. This study identified total vaulter energy at maximum pole bend to be associated with maximising total energy over the course of the vault and therefore maximum transition of energy through the initial vault phases that serve to influence overall pole vaulting performance. Chapter 6 focuses on the development of the pole GRF data collection during a vault
(which has been used here to calculate the energy stored in the pole) as a biomechanical analysis tool alone as a method of determining performance indicators.
Are pole ground reaction forces indicative of performance in elite pole vaulters?
6.1 INTRODUCTION
Recorded pole ground reaction forces (GRF) have previously been used to represent the total reaction at the base of the pole, with the recorded reaction force then used to estimate energy stored in the pole (Arampatzis et al., 2004; Schade et al., 2006). However, no research has examined the raw force profiles, nor investigated how they might be used to assist biomechanical technique analysis. The aims of this study were to analyse the pole GRFs to identify variables that may be used to describe success in the pole vault.

In a case-study investigation examining pole GRFs, Doyle and colleagues (2011) found that variation in approach velocity, via increased approach distance, resulted in demonstrated differences in pole kinetics. Although an examination of only a single elite vaulter, the results indicated that increasing the approach velocity leads to distinct changes to the pole GRF profiles. The majority of these changes occurred in the two horizontal planes (X&Y) with the pole at maximum bend (deformation), and produced consistent characteristics that could be used as temporal markers for analysis across approach distances. Doyle et al., (2011) recommended the use of pole kinetics as a potential method of segmenting the vault into discrete phases and highlighted that further work was required to determine the effectiveness of this testing modality as a tool for distinguishing performance characteristics.

Ground reaction forces have been shown to be an influential biomechanical analysis tool in many sports. GRFs have been previously used to identify critical factors for running, long jump and triple jump performance (Hamill, Bates, Knutzen, & Sawhill, 1983; Novacheck, 1998; Perttunen, 2000; Seyfarth, Friedrichs, Wank, & Blickhan, 1999). These studies provide exemplars for how GRF can be utilised as an integral component in the biomechanical analysis of athletic techniques. As well as displaying a typical schematic representation of the force components, GRFs also display the resultant mechanical output of the motor pattern being investigated. Pole GRF’s in pole vaulting have previously been used to calculate the energy stored within the pole (Schade et al., 2006), although this methodology did not consider individual pole specific characteristics as input criteria. Additionally, pole kinetics have not been previously used to differentiate discrete phases of the vault and have only stated an apparent difference between male and female athletes (Arampatzis et al., 2004; Schade et al., 2006). With the testing set-up adopted in this study it was possible to record and
analyse the individual force components directed by the base of the pole into the pole plant box (pole GRFs).

Pole GRFs have not previously been used to distinguish between vaulting performances. The aims of this study were to examine several variables relating to pole GRFs and to examine male and female mass normalised force profiles. These variables were evaluated against the peak jump height with participants grouped by gender. A final aim was to describe critical event timings using the raw force profiles, with the goal to further use these descriptors to assess differences between male and female vaulters.

It was hypothesised that males vaulters will display significantly greater normalised pole GRF and impulse compared with females at peak anterior-posterior horizontal (X), maximum pole bend and peak vertical (Z) force, whilst displaying similar relative timing at key discrete events. This trend will also be observed in continuous waveform data, where males will present with greater normalised pole GRF compared with females. Finally, it was hypothesised that the maximum vertical force and overall total impulse will be positively correlated with peak COM height.

6.2 METHODS

6.2.1 Participants
A total of eight pole vault athletes, four males (age 25.7 ± 6.2 years, height 187.8 ± 4.7 cm, mass 83.6 ± 5.4 kg) and four females (age 21.1 ± 5.9 years, height 170.5 ± 4.7 cm, mass 59.6 ± 2.9 kg) who were national level or higher (including world championship and Olympic Games titles or experience) participated in the study. Approval was obtained from the Australian Institute of Sport Ethics Committee (20110401) and The University of Western Australia Human Research Ethics Committee (RA/4/1/5172) (Appendix A). All participants were provided with study information sheets and provided written informed consent prior to study participation.

6.2.2 Procedures
Data collection for this investigation was conducted concurrently with the data collection of the previous chapter; with a more detailed data collection methodology outlined in Chapter 3.3 (extended methods). The pole GRFs were recorded using the 3D pole plant box described fully in Chapter 3.1. For each pole vault attempt pole GRFs
were recorded for a five second epoch that enveloped the jump. An LED synchronisation light automatically displayed following initiation of the kinetic data recording and ceased display at the end of the five second data collection epoch. Six video cameras were positioned to encompass the vaulting volume, with the LED observable in each cameras field of view to facilitate post testing video and force data synchronisation.

6.2.3 Data Treatment

Data treatment was performed using a custom designed computer program developed in IGOR (WaveMetrics IGOR Pro 6) software by the School of Physics at The University of Western Australia. The pole GRF traces were filtered using a binomial smoothing function set at a level of 150, as selected based on an inspection of a Fast Fourier Transform of the raw data. Peaks of each force component and the times at which they occurred were calculated. The impulse was also calculated from the force traces and this represented the integral or the area underneath the force/time curve. For the waveform analysis, the force curves were time-normalised from initial pole plant until full pole extension, with the point of maximum pole bend fixed to 50% of the normalised time.

Statistical analyses were calculated in IBM® SPSS® Statistics 21 (IBM Corporation, Armonk, NY, USA). Independent samples t-tests were used for differences between male and female pole vaulters for the selected variables with a significance level set α<0.05. All jumps were included in analysis with mean data for each vaulter compared. A multiple linear regression was conducted to determine variables correlated to peak height.

The open source one dimensional statistical parametric mapping (SPM) package (SPM1D (33)) was used to statistically compare continuous waveform data using Matlab® (Ver. 7.8.0.347). The SPM was computed at each point in the normalised time series for each force component and total force data sets, forming a statistical parametric map (Pataky, 2010; Robinson et al., 2014). This methodology has been used previously in comparison of knee joint kinematics to determine the influence of direct and inverse kinematic modelling procedures during cutting manoeuvres (Robinson et al., 2014). Unlike traditional statistical analyses methods that assess for differences between single value discrete time points, this statistical methodology provides a method for comparing two continuous data series (e.g. joint angles across stance) and identifies areas of
waveform data that are significantly different. The statistical significance value for SMP analysis was also set to $\alpha<0.05$.

6.3 RESULTS AND DISCUSSION

6.3.1 Ground Reaction Force Data Overview

A representative example of the tri-axial force components and the resultant force for one pole vault trial is depicted in Figure 6.1. This can be segmented into phases based on the temporal location of the peak force and maximum pole bend. It can be seen that there is a relatively insignificant amount of force recorded in the lateral (Y) direction indicating minimal horizontal forces are produced perpendicular to the approach direction. The initial impact peak and subsequent vibrations in the force profiles can be attributed to the dynamic impact response of the pole end into the plant box. These attenuate reasonably quickly and for the purpose of this study, data peaks were removed during filtering, as it was not within the scope of this investigation to examine the resonance causing the ringing effect at impact.

Figure 6.1. Representative graph of the typical force profile for Anterior-Posterior (forceX), Lateral (forceY), Vertical (forceZ) components and the resultant pole GRF (force_mag).
Consequently, for the purposes of this study, these impact peaks were considered to constitute measurement artefact. The majority of the initial force occurs in the anterior-posterior (X) direction; this direction of the approach causes a decrease in horizontal velocity of the vaulter as energy is transferred into the pole. Although the anterior-posterior force component remains positive throughout the vault, the vaulter is continuously decelerating (Morlier & Mesnard, 2007). The vertical (Z) component of force increases gradually as the vaulter moves closer to being directly above (superior to) the load cell and plant box. As the vaulter comes to be situated above the plant box their motion is almost entirely vertical and this is observed with the horizontal force decreasing towards zero and the vertical forces reaching their peak due to the acceleration of the vaulters COM vertically. Without the ability for direct comparison these observed force profiles appear similar to those presented in previous literature (Arampatzis et al., 2004; Schade et al., 2006).

In a pilot study where one vaulter’s force profiles were analysed from three different approach lengths (Doyle et al., 2011), distinct differences were observed across the three approach types. Doyle et al, (2011) reported that force profiles at the base of the pole changed with increased approach length due to the increase in velocity at take-off. The large proportion of these changes occurred in the horizontal planes with smaller changes observed in the vertical direction. This finding was not unexpected given that a vaulter must apply similar vertical forces regardless of approach method employed. The force profiles investigated in this study (Figure 6.1) show obvious differences to those presented by Doyle et al. (2011). Although the subject used in Doyle et al’s., study (2011) also participated in the current study, the differences can be explained by specific changes in techniques occurring in the elapsed time between the data collection periods of the two studies (Personal Communication – Alex Parnov, WAIS Pole Vault Coach). The vaulter in Doyle et al. (2011) study positioned the pole on the opposite side of the plant box compared with the trials analysed in the present investigation. The obvious differences in the horizontal forces are a result of the pole making contact with the side of the plant box as it was bending in Doyle’s study. Whereas this contact does not occur with the altered technique used by the vaulter in the present study. Subsequently, varying force profile characteristics are recorded at the two testing sessions. Additionally, the phase breakdown of the force profiles are not compatible between the two investigations as the key critical points identified in the force traces are inconsistent, resulting in a new phase breakdown of the forces for this study using the
peak forces in the anterior-posterior and vertical directions, in combination with the timing of maximum pole bend (MPB).

6.3.2 Discrete Comparisons of Male and Female Pole Vaulters
Discrete pole GRF data have not been previously presented or used as a comparative variable to delineate between vaulters. Force peaks normalised to vaulter body mass are presented in Table 6.1. No significant differences were found between the male and female vaulters on assessment of these mass-normalised forces. The phases in the force profiles were defined as Phase A (pole plant (PP) to the peak in anterior-posterior force), Phase B (peak anterior-posterior force to MPB), Phase C (MPB to peak in vertical force) and Phase D (peak in Z force to force end) and are represented in Figure 6.2. The timing of the phases determined in the force profiles are presented in Table 6.2 with no significant difference found between males and females.

Figure 6.2. Representative graph of typical force profile with phase breakdown; Phase A (pole plant to the peak in anterior-posterior force), Phase B (peak anterior-posterior force to MPB), Phase C (MPB to peak in vertical force) and Phase D (peak in vertical force to force end).
Table 6.1. Average and SD for normalised force of 4 male (1-4) and 4 female (5-8) elite pole vaulters.

<table>
<thead>
<tr>
<th>Vaulter</th>
<th>Force X (N.kg(^{-1}))</th>
<th>Force Y (N.kg(^{-1}))</th>
<th>Force Z (N.kg(^{-1}))</th>
<th>Force Total (N.kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.89 (0.12)</td>
<td>1.40 (0.50)</td>
<td>13.81 (0.26)</td>
<td>14.08 (0.33)</td>
</tr>
<tr>
<td>2</td>
<td>8.95 (0.22)</td>
<td>1.09 (0.61)</td>
<td>16.19 (0.39)</td>
<td>16.49 (0.30)</td>
</tr>
<tr>
<td>3</td>
<td>10.97 (0.22)</td>
<td>1.30 (0.16)</td>
<td>15.54 (0.27)</td>
<td>16.19 (0.57)</td>
</tr>
<tr>
<td>4</td>
<td>9.74 (0.29)</td>
<td>1.01 (0.23)</td>
<td>14.07 (0.19)</td>
<td>14.43 (0.13)</td>
</tr>
<tr>
<td>Male</td>
<td>9.89 (0.83)</td>
<td>1.20 (0.18)</td>
<td>14.90 (1.15)</td>
<td>15.30 (1.22)</td>
</tr>
<tr>
<td>5</td>
<td>9.68 (0.16)</td>
<td>0.79 (0.37)</td>
<td>14.49 (0.18)</td>
<td>14.97 (0.28)</td>
</tr>
<tr>
<td>6</td>
<td>8.47 (0.25)</td>
<td>1.33 (0.70)</td>
<td>15.67 (0.37)</td>
<td>15.89 (0.37)</td>
</tr>
<tr>
<td>7</td>
<td>9.06 (0.33)</td>
<td>1.49 (0.43)</td>
<td>15.43 (0.08)</td>
<td>15.49 (0.10)</td>
</tr>
<tr>
<td>8</td>
<td>8.88 (0.29)</td>
<td>1.17 (0.82)</td>
<td>15.09 (0.61)</td>
<td>15.24 (0.58)</td>
</tr>
<tr>
<td>Female</td>
<td>9.02 (0.50)</td>
<td>1.19 (0.30)</td>
<td>15.17 (0.51)</td>
<td>15.40 (0.39)</td>
</tr>
</tbody>
</table>

Table 6.2. Phase time and total time for males and females.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Phase A (s)</th>
<th>Phase B (s)</th>
<th>Phase C (s)</th>
<th>Phase D (s)</th>
<th>Total (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>0.22 (0.05)</td>
<td>0.36 (0.07)</td>
<td>0.15 (0.04)</td>
<td>0.43 (0.08)</td>
<td>1.15 (0.11)</td>
</tr>
<tr>
<td>Female</td>
<td>0.23 (0.04)</td>
<td>0.33 (0.03)</td>
<td>0.16 (0.04)</td>
<td>0.44 (0.03)</td>
<td>1.16 (0.02)</td>
</tr>
</tbody>
</table>

The timing of force peaks were used to delineate key phases in which positive impulse (work) was calculated. Average horizontal and vertical impulse and the overall resultant impulse are presented in Table 6.3. The overall total impulse can be explained as an estimation of the work done on the pole from initial impact to force end. Again, no significant differences were found between male (27.34±2.65 N.s) and female (27.39±0.96 N.s) vaulters, though the horizontal (male 10.71±0.12 N.s v female 9.51±1.16 N.s) and vertical (male 23.00±2.92 N.s v female 23.81±1.55 N.s) force components approached significance.

Table 6.3. Phase and total impulse for males and females.

<table>
<thead>
<tr>
<th>Impulse</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase A (N.s)</td>
<td>3.11 (0.56)</td>
<td>2.97 (0.78)</td>
</tr>
<tr>
<td>Phase B (N.s)</td>
<td>5.85 (0.77)</td>
<td>5.03 (0.26)</td>
</tr>
<tr>
<td>Phase C (N.s)</td>
<td>1.24 (0.18)</td>
<td>1.29 (0.18)</td>
</tr>
<tr>
<td>Phase D (N.s)</td>
<td>0.50 (0.33)</td>
<td>0.22 (0.37)</td>
</tr>
<tr>
<td>Total (N.s)</td>
<td>10.71 (0.12)</td>
<td>9.51 (1.16)</td>
</tr>
<tr>
<td>Iz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase A (N.s)</td>
<td>1.97 (0.66)</td>
<td>2.08 (0.22)</td>
</tr>
<tr>
<td>Phase B (N.s)</td>
<td>7.25 (0.86)</td>
<td>6.83 (0.82)</td>
</tr>
<tr>
<td>Phase C (N.s)</td>
<td>4.11 (1.02)</td>
<td>4.64 (1.34)</td>
</tr>
<tr>
<td>Phase D (N.s)</td>
<td>9.67 (2.18)</td>
<td>10.26 (0.52)</td>
</tr>
<tr>
<td>Total (N.s)</td>
<td>23.00 (2.92)</td>
<td>23.81 (1.55)</td>
</tr>
<tr>
<td>Itot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase A (N.s)</td>
<td>3.71 (0.83)</td>
<td>3.66 (0.76)</td>
</tr>
<tr>
<td>Phase B (N.s)</td>
<td>9.46 (1.11)</td>
<td>8.58 (0.78)</td>
</tr>
<tr>
<td>Phase C (N.s)</td>
<td>4.33 (1.02)</td>
<td>4.84 (1.32)</td>
</tr>
<tr>
<td>Phase D (N.s)</td>
<td>9.74 (2.19)</td>
<td>10.31 (0.53)</td>
</tr>
<tr>
<td>Total (N.s)</td>
<td>27.24 (2.65)</td>
<td>27.39 (0.96)</td>
</tr>
</tbody>
</table>

As previously noted, minimal medio-lateral forces were recorded during the vault and subsequently it was excluded from further analysis. The observable differences for the anterior-posterior impulse in phase B (male 5.85±0.77 N.s v female 5.03±0.26 N.s) and the total phase (male 10.71±0.12 N.s v female 9.51±1.16 N.s) can be explained by the...
males having greater energy in their approach and providing greater force in the anterior direction in order to transfer energy into the pole.

These results show that males and females employ similar force production strategies. The limited sample size available for this investigation may explain the lack of between group differences. Closer inspection of individual athlete results indicate that there is within group variability although further research is required to determine the extent of this variation across a greater sample size. Further, when normalising to the mass of the vaulter, the pole GRF variables become more difficult to identify. This result suggests that once corrected for mass, males and females produce similar results.

6.3.3 Comparison of Force Curves
To gain a full understanding of the effects of the kinetics across the entire vaulting phase, it is necessary to investigate and provide direct comparisons of the entire waveform data. With a statistical comparison of curves it is possible to view the complete trial and highlight temporally where the two curves statistically deviate from one another.

To highlight variations in waveform data throughout the vault, an SPM analysis between male and female vaulters was performed. This provides the ability to analyse continuous data across the entire phase of interest and temporally identify where during phase, the two waveforms significantly deviate from each other. Results of the SPM are presented in Figure 6.2; the average force curves for males and females for anterior-posterior (a), lateral (b), vertical (c) and the resultant force (d) are presented on the left side and the calculated SPM for each comparison directly to the right. All forces have been normalised to the participant’s body mass. As previously identified, the majority of the GRF at the base of the pole is present in the form of the anterior-posterior (a) and the vertical (c) force components. Taking into account the small lateral force (b) recorded, with the maximum not exceeding 100N, it was deemed that this was insignificant to the overall performance of a vault. While there visually appears to be an observable difference for males presenting with higher anterior-posterior forces than females in the first 40% of the vault, this difference was not deemed statistically significant. It can be seen in the vertical GRF (Figure 6.3c) that females displayed greater pole GRF production ($p=0.014$) during the final 10% of the vault compared with the male vaulters.
Figure 6.3. SPM comparisons of average anterior-posterior (X), lateral (Y), vertical (Z) and resultant total pole GRF (ForceTotal) for males and females.
The normalised average force waveform data shows the similarities between the overall male and female force curves. While there are minor differences between the two curves, there is large overlap in standard deviations highlighting the large variation within groups. The similarity between males and females could be partially explained by the majority of the athlete pool analysed being influenced by the same coach, who will impart his own specific technical model. Despite this, there are also confounding variances resulting from individual nuances in the vaulter's techniques. Upon closer inspection of the individual athlete force traces there were observable differences within the male and female vaulters. Despite all vaulters being classed as high level, there was still distinct experience levels due to age differences within the group (both within the male and female groups) which likely lead to variable force profiles being exhibited.

The only area statistically meaningful difference identified between males and females when comparing the group average normalised waveform data, indicates a possible temporal shift in the timing of force application. Females continued to apply greater vertical pole GRF for a longer duration ($p=0.014$) (see 94-96% phase of Figure 6.3c) which may indicate that the males are able to rotate their body into the inverted position more effectively than females, thereby facilitating earlier transfer of energy from the pole, back to the vaulter, as the pole is straightening. This occurs during the last 10% of the pole phase which corresponds to the final extension of the pole, where females provide higher levels of vertical force with respect to their body mass just prior to pole straight. This difference in Figure 6.3c appears small and it is difficult to infer meaningful application to the vaulting manoeuvre. Once again; under closer inspection of the individual force profiles there were possible confounding differences between vaulters (across gender) during this pole straightening phase. Overall, there were no observable differences between the male and female groups, suggesting that the overall performance may not be distinguishable when assessing pole GRF in isolation and that, other variables that are likely to discriminate performance factors. Due to the relatively small sample size it was not possible to group the vaulters by pole GRF profiles. Greater subject numbers are necessary so that specific groupings of ability might be possible. Also; further investigation should also involve a more comprehensive analysis of individual vaulter pole GRF profiles, with the aim of describing the athlete’s specific technical strategy via an individual case study approach.
6.3.4 Predictors of Peak Height

Ultimately, successful pole vault performance filters down to the peak COM height reached by the vaulter. From distinguishing energy variables analysed in the previous chapter this investigation aimed to apply the same rationale to pole GRF force variables. The rationale for such an investigation is the potential for simple pole GRF readings to provide the biomechanist and coach with a rapid feedback tool for monitoring technical changes in the vaulters (as opposed to having to conduct a full 3D kinematic and kinetic analysis). Identifying variables that correlate with peak COM height from the pole GRF profiles, and relating them to the energetic variables from the previous study, provides a direct link between to these two independent yet interrelated analysis variables.

A multiple regression analysis was conducted that included variables which theoretically contribute to the peak COM height, combined with those variables utilised in the previous energy regression analysis. These variables included; the peak anterior posterior force, anterior posterior impulse up to MPB, vertical impulse up to MPB and the total overall impulse. For males a significant model emerged, $F(7,26) = 59.724$, $p<0.001$, whereby approximately 94% of the variance in peak COM height was explained by the predictors (adjusted $R^2 = 0.94$). The model accounted for the individual vaulters as independent variables, due to the varied number of vaults between them, and this proved to be the only significantly correlated variable ($p=0.008$). No significance was displayed for all other variables. For females, a similar significant model emerged, $F(7,39) = 20.684$, $p<0.001$, where approximately 78% of the variance in peak COM height was explained by the predictor input variables (adjusted $R^2= 0.78$). The individual vaulter again proved to be the only significantly correlated variable serving to influence peak height ($p<0.001$).

These results indicate that across male and female vaulters the largest determining factor contributing to vaulting performance from the force profiles is the differences between athletes. As would be expected, the performance level of the vaulter is significantly and positively correlated to the peak COM height reached; indicating the ability of the individual to utilise the applied force as a critical component. Due to the varying number of trials between vaulters, the athlete was added into the model as an independent variable. Due to the statistical model’s identification of the individual vaulters influence on the data (males $p=0.008$; females $p<0.001$), it is possible that the inclusion of the athlete as an independent variable diminished the possibility of
identifying significant variables from the force profiles. Pole GRF data is largely reliant on the mass of the athlete, so when normalising the force data to the athlete’s mass differences within the determining variables will be more difficult to distinguish. Of note however is that in the preceding study (Chapter 5), where differences were observed in the subject specific energy calculations between males and females, and there were also distinguishing variables for peak height, these variables did not translate through to the pole GRF analysis.

6.4 SUMMARY AND CONCLUSIONS

6.4.1 Review of Hypotheses

When GRF data was normalised to vaulter mass no significant differences were observed between male and female vaulters across all discrete variables analysed. No differences were found between males and females when determining the timing of the phases defined from the force profiles. Contrary to our hypothesis, for comparisons of waveform data females displayed greater force in the vertical direction during the final stages of the vault. At no time during the vault phase did male vaulters display significantly greater mass normalised force components than their female counterparts. Contrary to our hypothesis, that mass normalised horizontal force in the direction of the approach and the overall total impulse would be correlated to peak height, no significant predictors of the peak height reached were discovered from the pole GRF analysis other than the vaulter themselves.

6.4.2 Conclusions

Comparing male and female grouped data did not provide information that could be used to determine vaulting strategies or that could be matched to energy results. However under a more comprehensive analysis of individual differences it would be expected that vaulters show distinct characteristics. No significant variables were found that correlated pole GRFs to peak COM height or that could be used to deduce energy changes. However, pole GRF analysis does provide an additional non-invasive monitoring tool that can be used to examine the strategies applied by pole vaulters as an overall estimation of performance. Further examinations of pole GRFs during vaulting should focus on individual vaulters and their personalised results via case study analysis, which ultimately may assist in distinguishing performance characteristics in elite vaulters at a group level. This case study approach will be presented in Chapter 7.
using the pole GRF analysis along with the pole energy calculation and subject specific vaulter energy discussed in the previous chapters.
The Case Study of an Elite Female Pole Vaulter
7.1 A Case Study of an Elite Female Pole Vaulter

The fundamental objective of the pole vault event is to jump as high as possible to successfully clear the bar. The vaulter uses a flexible pole to assist them to jump over a horizontal bar, necessitating a complex interaction between the pole and vaulter to achieve a successful outcome. Performance in the pole vault is heavily reliant on efficient energy transfer throughout the vaulting manoeuvre. This energy is initially present in the form of kinetic energy (KE) which is subsequently transferred into elastic potential energy (EPE) as the pole compresses and finally gravitational potential energy (GPE) of the vaulter as the pole recoils. An overall representation of the energy flow through the vault is mirrored in the pole ground reaction forces (GRF).

In a unique approach to pole vault biomechanical analysis, this study will present a case study approach incorporating both individual specific energy components and pole kinetics. This case study analysis will form a comprehensive discussion-based analysis of critical factors associated with pole vault success. Given that the ultimate aim is height, the peak height reached by the vaulter’s centre of mass (COM) can be viewed as the best measure of success in vaulting. Providing specificity of input variables into the final analysis allows a more comprehensive individual analysis of the vaulter-pole system. Hence, the integration of the pole-specific data (presented in Chapter 4) with subject-specific energy calculations (Chapter 5) provides greater ecological validity of the results for the individual athlete being analysed.

To highlight the applicability of results in the preceding chapters, this study aims to provide a discussion-based analysis of critical vaulting variables as it relates to the performance outcomes of an elite female vaulter. Two vaults, with substantially different performance outcomes (4.72 m versus 4.43 m peak COM height), were selected for comparative analysis from the same female athlete. Individual discriminating factors are highlighted as potential causative factors serving to influence the overall performance outcome. The data presented in this case study incorporated the methods developed in previous chapters; the pole specific energy function developed in Chapter 4, the vaulter specific energy calculations presented in Chapter 5, and the pole GRF investigated in Chapter 6.

For the two vaults presented in this case study the vaulter used two different poles, both 4.45 m in length of fibreglass construction (Vault 1 used pole 7 and Vault 2 used pole 8
from Chapter 4). From the reported manufacturer flex ratings, the pole used in Vault 1 (22.1 flex) was softer than the pole used in Vault 2 (21.8 flex). The difference in the reported manufacturer flex ratings effectively indicated that there would be an expected 3 mm difference in deformation distance when applying a static 50 lb (22.7 kg) load to the centre. When attempting to replicate these flex values though (Chapter 4), both poles recorded the same deformation of 19.3 cm (giving a flex rating of 19.3). Both poles also recorded a pre-bend distance of 2.2 cm. The difference between the manufacturer reported flex value and recorded flex value from the static load test for these poles, represent what the athlete and coach would consider a substantial deviation from the expect stiffness of the poles. The dynamic bending trials (Chapter 4) showed similar properties in deflection between the two poles with a recorded difference of 5.9 N for the maximum force and 5.1 J for the maximum energy. Hence, there was found to be minimal observed difference in the bending characteristics of these two poles. The top hand grip heights were 4.28m and 4.31m respectively, which may have been one influencing factor that that slightly altered the stiffness feel of each pole by the vaulter.

When examining the two vaults temporally, it was observed that key events aligned closely. Further analysis post synchronisation showed the pole plant (PP), the timing of the maximum pole bend (MPB) and the pole full extension (PS) of the two vaults fell within one video field (0.02s) of the other (Table 7.1). Vault 1 displayed a slightly shorter timing epoch between PP and MPB, resulting in a marginally longer flight phase from PS to peak height (PH). This is consistent with the energy flow through the two vaults with less time to decrease energy and load the pole in Vault 1 leading up to MPB. However, these differences are minimal and this indicates that large variations in the timing within the vault were not a causative factor to explain differences in the vaulting performance.

Table 7.1 outlines a summary of discrete values associated with performance for both of the vault attempts, while Figure 7.1 illustrates the energy waveform data of the two vaults completed. Vault 1 achieved a peak COM height of 4.72 m against 4.42 m for Vault 2. There were minimal, yet consistent, observed differences in GRF between the two vaults (Figure 7.2), with Vault 2 displaying greater values for all variables apart from the peak X force (Table 7.1). These results are consistent with the findings of the preceding study (Chapter 6) where no kinetic variables were found to be significant
predictors of peak height. From observing the kinetics alone, the two jumps appear similar.

Table 7.1. Discrete variables from two vaults performed by the same vaulter

<table>
<thead>
<tr>
<th>Discrete Variable</th>
<th>Vault 1</th>
<th>Vault 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak COM Height (m)</td>
<td>4.72</td>
<td>4.43</td>
</tr>
<tr>
<td>Vaulter Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Energy Initial (J)</td>
<td>2574.2</td>
<td>2580.1</td>
</tr>
<tr>
<td>Total Energy MPB (J)</td>
<td>1392.6</td>
<td>1308.3</td>
</tr>
<tr>
<td>Total Energy PS (J)</td>
<td>2287.0</td>
<td>2196.8</td>
</tr>
<tr>
<td>Total Energy PH (J)</td>
<td>2874.0</td>
<td>2682.2</td>
</tr>
<tr>
<td>Energy Decrease (J)</td>
<td>1181.6</td>
<td>1271.8</td>
</tr>
<tr>
<td>Energy Increase (J)</td>
<td>1481.8</td>
<td>1373.9</td>
</tr>
<tr>
<td>Energy Gain (J)</td>
<td>300.2</td>
<td>102.1</td>
</tr>
<tr>
<td>Action (area under energy curve) (J.s.kg(^{-1}))</td>
<td>3300.1</td>
<td>3157.4</td>
</tr>
<tr>
<td>Pole Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPE In (J)</td>
<td>1307.7</td>
<td>1415.4</td>
</tr>
<tr>
<td>EPE Out (J)</td>
<td>1180.6</td>
<td>1285.9</td>
</tr>
<tr>
<td>EPE Loss (J)</td>
<td>127.1</td>
<td>129.4</td>
</tr>
<tr>
<td>Kinetics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Anterior-Posterior Force (N)</td>
<td>588.2</td>
<td>580.3</td>
</tr>
<tr>
<td>Peak Vertical Force (N)</td>
<td>866.1</td>
<td>883.3</td>
</tr>
<tr>
<td>Peak Total Resultant Force (N)</td>
<td>892.2</td>
<td>912.2</td>
</tr>
<tr>
<td>Anterior-Posterior Impulse (N s)</td>
<td>670.6</td>
<td>695.5</td>
</tr>
<tr>
<td>Vertical Impulse (N s)</td>
<td>1280.2</td>
<td>1310.5</td>
</tr>
<tr>
<td>Total Resultant Impulse (N s)</td>
<td>1559.0</td>
<td>1592.9</td>
</tr>
<tr>
<td>Phase Timing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial to PP (s)</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>PP to MPB (s)</td>
<td>0.58</td>
<td>0.60</td>
</tr>
<tr>
<td>PP to PS (s)</td>
<td>1.12</td>
<td>1.14</td>
</tr>
<tr>
<td>PP to PH (s)</td>
<td>1.58</td>
<td>1.56</td>
</tr>
</tbody>
</table>
Figure 7.1. Mass normalised total vaulter energy (a), gravitational potential energy (b), translational kinetic energy (c) and rotational kinetic energy (d) for vaulting phase from initial to peak height. One female vaulter’s best and worst performing vaults. 50% is the point of maximum pole bend for both the energy and kinetic curves.
Figure 7.2. Total force, X (anterior-posterior) force and Z (vertical) force from mid final stride flight phase to peak height. The vertical line encompasses the MPB for both vaults with the force profiles synchronised to pole plant. The lateral (Y) force profile was not presented as it displayed minimal force.

Examination of the continuous energy data reveals that the vaulter displayed almost identical initial energy across both jumps. As such, the external input variables prior to vault initiation may be considered to be the same for both vaults. This is supported in Table 7.1 where the initial energy of the vaulter is similar, suggesting that the performance outcome differences are likely attributed to the actions occurring during the pole interaction phase of the vault. This research found that the initial energy of the vaulter was not a significant factor to performance when observing multiple vaults from a similar sample (Chapter 5), which is supported by literature reporting changes in approach velocity do not differentiate between vaulters of a similar performance level (Mueller & Hommel, 1997; Young & Yeadon, 1997).

It can be speculated that there is a small difference in the pole GRF when the pole impacts the plant box (PP) of the two vaults (Figure 7.2). Whilst peak impact forces during this phase have been removed as a result of the filtering process employed, the difference is visually consistent across the anterior-posterior and vertical force directions, and is also observed in the total force calculated. Greater impact peaks are also displayed for the poorer jump (Vault 2). This may indicate that the pole plant
mechanics in Vault 2 was not as effective, due to the higher impact forces compared with Vault 1, although this finding does not appear to negatively influence the subsequently derived force or energy data.

The total energy of the vaulter is increased for Vault 1 compared with Vault 2, from approximately 25% of the vaulting phase onwards (Figure 7a). This increase is likely attributed to a better COM positioning in relation to the pole facilitating more efficient transfer of energy later in the vault. The translational KE remains similar in both vaults over the entire phase suggesting that performance factors are not observed in this energy component. It is likely that, when the initial translational KE is similar for two vaults, the horizontal velocity is consistently maintained between vaults.

The difference in the peak height reached by the vaulter is represented in the waveform through the GPE and the total vaulter energy. The GPE of the vaulter is similar for both vaults until after MPB where Vault 1 GPE increases at a faster rate (Figure 7.1b). A difference between the vaulter energy at MPB with Vault 1 greater than Vault 2 is then observed. Results from an earlier investigation (Chapter 5) concluded that the total vaulter energy at MPB was a significant predicting variable to performance. This case study supports this finding, with the more successful vault (Vault 1) displaying higher vaulter energy at MPB. Vault 1 also displays a smaller energy decrease (difference between initial and MPB total vaulter energy) compared with Vault 2, resulting in the greater total energy at MPB for Vault 1 (Table 7.1).

Vault 1 displays decreased EPE stored in the pole compared with Vault 2 and also a smaller EPE recovered from the pole. The vaulter compressed the pole further in Vault 2, despite this pole having a stiffer manufacturer flex ratings. However, the replicated static load test and the dynamic trials demonstrated that both poles had similar elastic deformation properties. The slight increase in grip height (3 cm) may have assisted with the greater pole bend in Vault 2, resulting in greater EPE stored during the early period of the vault (leading up to MPB). The EPE in the pole was not found to be a significant predictor of height in the preceding studies (Chapter 5) with this case study returning higher EPE values in the less successful vault. Pole energy (EPE) calculations do consider the energy lost during pole bending for each individual pole. In this case study,
Figure 7.3. Sagittal plane sequence from approximated maximum pole bend to peak COM height at temporal points 0.58s; 0.82s; 1.0s; 1.22s and 1.54s from pole plant.
Figure 7.4. Posterior view sequence from approximated maximum pole bend to peak COM height at temporal points 0.58s; 0.82s; 1.0s; 1.22s and 1.54s from pole plant.
the energy lost in the pole appears similar for both vaults and subsequently, no inference regarding overall performance and EPE can be made between these two vaults.

An inherent feature of working closely with elite athletes is the necessity to relate data back to the visual representation of the technique (e.g. via video review). The technique differences in the two vaults examined in this case study (specifically after MPB) are visually depicted in Figures 7.3 and 7.4.

Figure 7.3 and 7.4 presents a photo sequence, at distinct time points, from MPB through to PH in both the sagittal and posterior planes, respectively. Vault 1 is presented on the left and Vault 2 on the right, with both sequences temporally synchronised to PP. Whereas the initial phases of the vault are similar for both jumps, differences between the two vaults are distinguishable after MPB. Figure 7.3c displays the better positioning of the athletes COM, creating a more efficient transfer into an inverted position (Figure 7.3d). There are some small observable differences within the sequential kinematics that are reflected in the rotational KE (Figure 7.1d), as discussed in Chapter 5. While these kinematic influences on overall energies are minimal these rotations of the vaulter about the pole can be clearly observed in the photo sequences of Figures 7.3 and 7.4. Due to the observed changes in energy profiles it is speculated that the vaulter in this case study is able to effectively move into the inverted position, due to optimal use of internal joint moments (not directly measured) within the successful vault. The vaulter has effectively optimised COM position with respect to the pole-COM distance, thereby maximising the return of energy from the pole as the line of action or tracking of the COM is closer to the pole.

The photo sequences in Figure 7.3 and 7.4, depicting differences between vault body rotations from MPB [(a) through photos (b) and (c)] visually highlight the more efficient transfer into the inverted body position achieved in Vault 1 (left graphs). The inverted position is where the vaulter is able to effective rotate about the pole (as per the double pendulum theory described in Chapter 2) such that they are upside down during the pole extension phase. This action aims to align the vaulter’s body position with the line of action of the pole extension to achieve greater vertical height. The still sequences presented support the view that in Vault 1 (greater height), the vaulter was
able to facilitate more effective the return of energy from the pole, via optimal body positioning.

The Action (area under the total energy curve) was found to be significantly correlated to PH (Chapter 5) and the observed difference from these two vaults also reflects this. Vault 1 also displays a greater energy increase (difference between MPB and PH total vaulter energy) and overall energy gain (difference between initial and PH total vaulter energy) to eventually reach greater maximum total vaulter energy at PH (Table 7.1). The greater energy increase and gain may lead to the longer temporal measures in the final phase of the vault leading to the increased height achieved.

From the EPE results in this case study, and relating them to the total vaulter energy through the vault, it maybe speculated that there is a trade-off between the energy stored into the pole and the overall vaulter energy. These changes are minimal and the result of the vault is more likely dependent on factors not observable in pole GRFs. Further investigation is necessary to identify if excessive pole bend is potentially detrimental to performance where it results in a corresponding reduction in the vaulter's energy leading up to MPB.

Aspects of the vaulting manoeuvre not accounted for in this investigation are the vaulter inter-segmental joint kinematics and we now hypothesise that it is in these variables where optimal performance factors will likely be distinguished. It can be speculated that differences in recruiting of joint musculature and internal joint kinetics through the vault may lead to segmental joint energy variation resulting in less than optimal performance. Further examination of these variables and the manner in which athletes are able to time their kinematics relative to the pole kinetics, while beyond the scope of this applied research, warrants further investigation.

From the developed methodologies and the results presented in the previous studies of this thesis, a more complete analysis of pole vaulting is now possible. This has been represented in this case study discussion via an incorporation of the overall energy of both the vaulter and the pole, together with the pole kinetics. Individually specific energy calculations and pole analysis provide a comprehensive addition to biomechanical analysis of the pole vault event. Performance is the ultimate goal, with
the ability to determine critical variables associated with improved jump heights being of great importance. This has not previously been a focus of research in pole vaulting. Although time consuming, difficult and beyond the scope of the work presented in this thesis, the incorporation of vaulter joint kinematics and kinetics is required to enable a comprehensive description of factors contributing to optimal pole vaulting performance.
Summary and Conclusions
8.1 SUMMARY

This research set out to undertake three primary investigations presented as three separate chapters. The thesis aims were to combine pole and athlete specific information into a full mechanical analysis of the energy and pole ground reaction forces in elite pole vaulting. The structure aimed to address the following issues that have yet to be addressed in the field.

1) The poles used in the pole vault event are characterised by generalised measures that do not fully represent their mechanical bending properties. A method of characterising these poles, that closely represents pole behaviour during a dynamic vault is required as pole behaviour is likely different during dynamic, as compared with statically loaded, conditions. Importantly, athletes and their support staff currently rely on the rating scales provided by pole manufacturers, established using static commercially sensitive testing methodologies. Pole behaviour, when tested across different bending regimes with an open source methodology, will facilitate enhanced understanding of the dynamic mechanics of pole vault manoeuvres.

2) Body segment inertial parameter information is commonly estimated using indirect methods (regression tables) that may not be drawn from samples reflecting the target population (e.g. general population versus elite athletes). Subsequently, direct (subject-specific) BSIP measurement from the individual athlete is clearly preferable over standard regression method estimations (indirect approaches). There is a need to incorporate athlete specific measures into analysis and to determine the effect on energy calculations in a dynamic situation.

3) Finally, pole ground reaction force investigations are scarce in the pole vaulting research domain and there has been no examination of their potential for distinguishing the performance strategies of pole vaulters.

This research outlines specific pole vaulting analysis approaches that provide greater depth of analysis than currently available to researchers. These approaches enable pole and athlete specific energy calculations to be incorporated into a comprehensive
biomechanical analysis of the pole vault. This will assist in the identification of causative factors contributing or inhibiting successful vaulting performance.

8.1.1 The Dynamics of the Vaulting Pole
This study was designed as a characterisation study that involved developing rigorous and robust pole testing methodologies. The aim was to develop more complex testing methods that better characterise the elastic properties of poles than the current manufacturer rating system across different load applications.

The initial stages of this study involved the custom design of a pole bending system for the production of load-deformation data on pole vault poles. This system was developed, allowing pole specific characteristics to be analysed under different bending regimes (quasi-static and slow dynamic) that were more representative of the pole bending behaviour during a real vault. All subsequent data for this investigation was collected using this methodology. Two methods of characterising poles were developed. A bilinear method provided a simplistic description of the load-deformation relationship that could characterise poles using four coefficients; the two slopes and the force and displacement location of the corner point. A more complex method involved the creation of a custom fitting function using seven pole specific coefficients that accurately reproduced the load-deformation curve for each pole. The coefficients required to obtain this characterisation indicated that methods used by manufacturers to establish in-house ratings did not adequately reflect the pole bending mechanical properties.

The hypotheses for this study were:

*Poles will display non-uniform bend when determining their deformation under different loads*
Non-uniform bending characteristics were evident for the load-deformation curves in both quasi-static, and slow dynamic, loading conditions. The bending curves were consistent across all poles depicting a complicated relationship for pole bending.

*Higher pole energy storage capabilities will be displayed during slow speed dynamic bending when compared with quasi-static measures*
The fitting function developed was used to calculate the energy stored, recovered and lost during pole bending that was specific to each pole. Greater energy storage was displayed for poles measured using the slow-dynamic bending methodology, compared with the quasi-static testing approach ($p=0.04$).

The percentage of energy lost through the pole in bending will be higher during slow dynamic, compared with quasi-static, bending regimes.

The percentage of energy lost between loading and unloading of the pole was significantly greater in the slow dynamic bending regime compared with the quasi-static ($p<0.001$).

### 8.1.2 Energetic measures as performance indicators: Do body specific inertial parameters effect energy calculations in male and female pole vaulters.

The aim of this study was to provide performance based outcomes to pole vaulting through an analysis of energy throughout the vault. More specifically, we investigated five indirect body segment inertial parameter methodologies and compared the results against direct athlete specific measurements obtained using a DXA method (subject specific ground truth BSIP). We further assessed the effect of BSIP input variation on the sensitivity of calculated rotational KE and total energy. Gender differences in identifying critical variables of performance in elite vaulters was also investigated using 67 vault trials from eight athletes.

The hypotheses for this study were:

There will be significant differences between segment mass and COM location determined using the DXA method when compared with the five indirect estimation methods.

Significant differences were exhibited between the DXA method and the five indirect calculation methods for both segment mass and the segment COM location across multiple segments for both males and females. The modified Chandler indirect method displayed the greatest variation in BSIP results when compared with the DXA derived values.
There will be differences in the total vaulter energy and rotational KE calculated with the DXA method compared with the five indirect methodologies. The indirect Chandler method was the only method where differences in BSIP data influenced downstream energetic calculations, where rotational KE was affected in the male vaulters. The Chandler method once again displayed the greatest variation to the DXA values for male vaulters when assessing the BSIP influence on total vaulter energy calculations. Variation to DXA derived outputs were also found between the DXA, and the Yeadon and Zatsiorsky Geometric Model methods, however these were of a lower magnitude than the Chandler outputs.

When calculating mass normalised energy parameters using only the DXA method:
(a) Males will exhibit greater total vaulter energy compared with females at each of the time points of the vault; initial, maximum pole bend, pole straight and peak height, as well as for calculated values of energy changes between phases; energy decrease, increase and gain
Males were found to produce significantly greater total body energy than females for initial, pole straight, peak height and gain variables. However, no such relationship was observed for energy at MPB or the energy decrease.

(b) From a comparison of waveform data for the energy components of the vaulter (translational KE, rotational KE, GPE and total), and the overall total energy (incorporating EPE) will be significantly greater in male vaulters compared with females
Continuous (waveform) data comparisons did not support our hypothesis that male vaulters would display greater higher energy values (translational KE, rotational KE, GPE, total vaulter energy and overall total energy), when compared with female vaulters. Gravitational potential energy was the only energy component to display significant between gender differences during 0-16% and 58-100% time phases of the vault ($p=0.013$, $p<0.001$).

(c) Initial KE and overall energy will be positively correlated with peak height
Contrary to our expectation, Initial energy was not correlated to performance (achieved COM peak height). Only the overall energy value (Action) (males $p<0.001$, females
and the total vaulter energy at maximum pole bend (males $p=0.003$, females $p=0.024$) were found to be significant predictors of performance.

### 8.1.3 Are pole ground reaction forces indicative of performance in elite pole vaulters?

The aim of this study was to provide a description of the vaulting strategies employed by male and female pole vaulters with respect to pole ground reaction forces. Discrete analysis of key pole GRF events, combined with continuous force profile differences, enabled variables correlated to peak height to be investigated. Pole ground reaction forces were recorded for four male and four females’ elite pole-vaulters in a total of 67 vaults.

The hypotheses for this study were:

**Male vaulters will display increased normalised force and impulse at discrete phase points; peak anterior-posterior force, maximum pole bend and peak vertical force, when compared with female vaulters**

No significant differences were displayed between males and females across any of the discrete comparisons.

**There will be no significant difference between males and females in the absolute timing of discrete time points in the force profile; peak anterior-posterior, maximum pole bend and peak vertical**

There were no differences in timing strategies employed by males and females across the force phases.

**Mass normalised anterior-posterior, lateral, vertical and resultant values will be higher in males compared with females across the entire vault (waveform SPM analysis)**

At no stage over the force profile did males exhibit greater values than females for all force components. Contrary to our hypothesis, females displayed significantly greater ground reaction force in the final 10% of the pole extension phase.

**Maximum vertical force and overall total impulse will be positively correlated with peak height in all vaulters**
No correlation existed between peak height reached and any variable derived from the ground reaction force profiles.

8.2 CONCLUSIONS

The three independent yet related studies presented in this thesis shared the common aims of increasing specificity of input variables to improve the understanding of the pole vault event. Previous research investigating pole vaulting has focussed on the vaulter and pole in isolation while using generic BSIP information for the participant sample. No subject or pole specific energy calculations have been developed or tested and the introduction of pole ground reaction force is a relatively new focus of research in the area.

The initial study, described in Chapter 4, involved the development of a pole bending system that provides the ability to characterise specific poles using two different bending regimes; quasi-static and slow dynamic. This characterisation is more closely related to the pole’s behaviour during a vault, particularly when compared with the current static classification methodologies employed by manufacturers. The production of load-deformation curves from the developed testing regimes enabled the application of a modified fitting function based on published stress strain theory (Duncan & Chang, 1970) that provides pole specific coefficients to model the loading and unloading dynamics of the pole. From this fitting function a pole’s capacity to store and return energy was quantified, thereby establishing energy loss within the pole. The key findings from this study were that a more detailed testing methodology and classification rating of poles better represents the mechanical properties, and that the poles will behave differently, in terms of energy storage and return, under different loading conditions. The applied output of this study was a fitting function and pole specific coefficients that may be incorporated into dynamic pole vault analysis to assist researchers in estimating the poles contribution to the vault.

The purpose of Chapter 5 was to compare five different methods of indirect body segment inertial parameter calculation with a direct method based on data derived from dual energy x ray absorptiometry (DXA) scans of participants. Then, to use the DXA method in comparisons of energy components between male and female pole vaulters
with the aim of distinguishing variables that are correlated to performance. The significant differences found between the indirect methods and the DXA method denote that when investigating special populations, who’s BSIP may vary from normative population data, such as elite athletes, it is recommended that subject specific segment parameters are used whenever accessible. However, when comparing the effect of variation in derived BSIP on downstream energy calculation, not all indirect methods resulted in energy data that was significantly different to the DXA calculated energy results. The indirect Chandler model resulted in BSIP data that was least consistent with the DXA ground truth values, and these differences carrying through to rotational kinetic energy and total vaulter energy calculations. Significant differences were found between male and female pole vaulters at discrete time points during a vault although these were not necessarily consistent with those reported previously in the only other investigation of this type (Schade et al., 2004). This is likely attributed to the varied sample sizes and number of jumps analysed across the two studies. Other than gravitational potential energy, that suggested males displayed greater energy for take-off and in the last 40% of the vault compared with females, the energy component continuous data did not differ across genders. Finally, the total energy of the vaulter at maximum pole bend, and the area under the total energy curve, were identified as significant to performance in pole vaulting. The significance of maximum pole bend especially, implies that there may be an optimal positioning for the vaulter through this phase that could possibly allow for more efficient pole vaulting and return of energy to the vaulter from the pole.

The focus of Chapter 6 was to investigate pole ground reaction force as a performance determining analysis tool. If differences occurred in the force profiles between gender and variables could be distinguished that correlated to peak height, this may lead to better understanding of the important biomechanical determinates of the vault. Importantly, such a finding could be used to establish pole GRF as a useful near real-time feedback tool for coaches and athletes. Contrary to Chapter 5 there were no significant differences between males and females for force profiles discrete variables. Interestingly, females presenting greater mass normalised force briefly at approximately 90% of the pole bending phase. This is likely a result of time spent of the pole, although this difference is minimal and it is difficult to present with meaningful application at this time. The key finding from this study is that while investigation with pole ground
reaction forces are potentially still important, optimal performance characteristics may not be distinguishable from the force profiles alone, there that other factors in the vaulting manoeuvre that are likely contributing to vault performance.

The final chapter formed a discussion chapter, allowing for the comparison of two vaults, from one vaulter, with large differences in the resultant peak heights achieved. With no substantial differences in initial energy parameters noted and similar poles used in the two vaults, differences in the final height was postulated to result from variances particularly in the pole extension phases. Greater heights were suggested to revolve around the ability of the athlete to achieve a more optimal inverted body position for the more successful vault, allowing for a potentially greater effective return of the pole energy into the gravitational potential energy.

8.3 FUTURE RESEARCH

This investigation has examined the pole vaulting technique with increased specificity of input variables for the pole and the vaulter. The bending system used in Chapter 4 provided an effective design for pole bending that could be improved on. More careful and accurate dynamic bending methods could aid in minimising some of the difficulties associated with the slow dynamic protocol. While the sample of pole vaulters in this investigation was almost the entire population of elite pole vaulters in Australia, general conclusions are based entirely on this similar sample. It is recommended that future research incorporates larger sample numbers recruited from a more varied pole vaulting population. Further, incorporating vaulter kinematics to better determine where performance can be distinguished is an aspect unaccounted for in this research. The inter-relationship within the vaulter and their ability to position themselves relative to the pole clearly warrants further investigation.
References


156


APPENDIX A

Ethics

Information Sheet

Consent Form
TO: Dr Andrew Lyttle
FROM: Ms Helene Rushby
SUBJECT: Approval from AIS Ethics Committee
DATE: 27th April 2011

At the last meeting of the AIS Ethics Committee, held on the 19th of April 2011, the Committee gave
consideration to your submission titled "The use of a novel markerless athlete tracking system and 3
dimensional pole plant kinetics in the optimisation of elite pole vaulters". The Committee saw no
ethical reason why your project should not proceed.

The approval number for this project is 20110401.

It is a requirement of the AIS Ethics Committee that the Principal Researcher (you) advise all
researchers involved in the study of Ethics Committee approval and any conditions of that approval.
You are also required to advise the Ethics Committee immediately (via the Secretary) of:

- any proposed changes to the research design,
- any adverse events that may occur.

Researchers are required to submit annual status reports to the secretary of the AIS Ethics
Committee until completion of the project. Details of status report requirements are contained in the
"Guidelines" for ethics submissions.

This Approval is valid until the 31st of December 2011; re-approval will need to be sought should the
project continue past this date.

Failure to comply with the above will render ethics approval null and void.

If you have any questions regarding this matter, please don't hesitate to contact me on (02) 6214
1577.

Sincerely,
Helene Rushby
Secretary, AIS EC
Our Ref: RA/4/1/5172 19 December 2011

Dr Ralph James
Physics (School of)
MIBP: M013

Dear Doctor James

HUMAN RESEARCH ETHICS OFFICE – RECOGNITION OF ETHICS APPROVAL FROM ANOTHER HUMAN RESEARCH ETHICS COMMITTEE

Project: Energy contributions in successful pole vaulting and dynamics of the vaulting pole

Thank you for your correspondence enclosing the necessary documents to facilitate recognition of the ethics approval for the above project granted by an external Human Research Ethics Committee (HREC) registered with the National Health and Medical Research Council (NHMRC).

It is noted that you have ethics approval from Australian Institute of Sport Ethics Committee, approval number 2011/0401.

The UWA students and researchers identified as working on this project are:

UWA Researchers:

<table>
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<tr>
<th>Name</th>
<th>Faculty/School</th>
<th>Role</th>
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<tbody>
<tr>
<td>Dr Ralph James</td>
<td>Physics (School of)</td>
<td>Chief Investigator</td>
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<td>Associate Professor Jacqueline Alderson</td>
<td>Sport Science, Exercise &amp; Health (School of)</td>
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<tr>
<td>Mr Andrew Lyttle</td>
<td>Sport Science, Exercise &amp; Health (School of)</td>
<td>Co-Investigator</td>
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Student(s): Trenton Warburton - PhD - 2014287

Although: The University of Western Australia reserves the right to subject any research involving its staff and students to its own ethics review process, in this case, the Human Research Ethics Office has recognised the existing approval of the external HREC. The project is exempt from ethics review at UWA and the involvement of the above-listed researchers has been authorised. Any conditions for the recognition of the external HREC's existing approval are listed below:

Special Conditions

None specified

You are reminded that it will be the responsibility of the approving HREC to ensure compliance with all ethics requirements and to monitor and report on the project. However, should any relevant ethics issues arise during the course of the project, you should inform the Human Research Ethics Office of The University of Western Australia.

If you have any queries, please do not hesitate to contact Kate Kirk on (08) 6488 3703.

Please ensure that you quote the file reference – RA/4/1/5172 – and the associated project title in all future correspondence.

Yours sincerely

Peter Johnston
Manager
Human Research Ethics Committee
Project Title: Energy Contributions in Successful Pole Vaulting and the Dynamics of the Vaulting Pole

Principal Researchers: Ralph James (PhD), Andrew Lyttle (PhD), Trenton Warburton

**Purpose:** This research project aims to utilise information derived from a 3D instrumented pole plant box and 3D digitisation to understand the mechanics of the vault and discriminate critical features associated with the pole vault technique. This research would also be complemented by the novel implementation of accurate 3D tracking of the athlete’s body throughout the vault using innovative image reconstruction techniques.

**Procedures:** Testing will incorporate the collection from the instrumented pole plant box and image reconstruction set-up. 6 cameras will be placed around the pole vault pit for the 3D capture. Approach velocity will also be recorded for all trials using a 100Hz laser gun (Laveg, Germany). Within the testing phase, multiple trials will be performed using the vaulters full approach distance. The testing session will be conducted as a normal training session.

Participants will also be required to have a 3D body scan completed as well as a DXA scan. These are non-invasive scans and will allow the full reconstruction of the participant’s body in 3 dimensions that will then be used to calculate subject specific segment parameters.

**Risks:** You will not be required to do anything other than what you would normally do at training. The utmost care will be taken to avoid any injury occurrence.

**Benefits:** Summary results from the testing session will be provided to you as soon as possible. The proposed research project has a direct benefit in improving the performance and consistency of our targeted elite vaulters, ensuring continual success at the International level. Further, significant impact on results through the ability to monitor and quantify athlete movement in a non-invasive manner for all land-based sports. This represents a major breakthrough in the ability to effectively service these elite athletes from a biomechanics perspective.

**Confidentiality:** All data will be stored on the researcher’s computers in a secure location and not on any public computers. No direct subject identifiers will be used in any external publications or presentations without your direct permission.

**Subject rights:** You have the right to withdraw from this research study at any time without any consequences. You have the right to access your data from the testing at any time.
Project Title: Energy Contributions in Successful Pole Vaulting and the Dynamics of the Vaulting Pole

Principal Researchers: Ralph James (PhD), Andrew Lyttle (PhD), Trenton Warburton

This is to certify that I, ______________ hereby agree to participate as a volunteer in a scientific investigation as an authorised part of the research program of the Australian Sports Commission under the supervision of Andrew Lyttle.

The investigation and my part in the investigation have been defined and fully explained to me by the researchers and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided to me and has been discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.

- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.

- I understand that I am free to withdraw consent and to discontinue participation in the project or activity at any time, without disadvantage to myself.

- I understand that I am free to withdraw my data from analysis without disadvantage to myself.

- I understand that any data or answers to questions will remain confidential with regard to my identity.

- I certify to the best of my knowledge and belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.

- I am participating in this project of my (his/her) own free will and I have not been coerced in any way to participate.

Signature of Subject: _______________________________ Date: ___/___/___

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: _____________________________ Date: ___/___/___
APPENDIX B

Pole Bending System

Designs and Drawings
Load cell base design:

Load cell base sagittal view drawing:
Load cell base above view drawing:

Moving trolley design:
Moving trolley sagittal view drawing:

Moving trolley above view drawing:
Drawing of system components together on the track:
APPENDIX C

Pole Coefficients
All pole coefficients:

### Quasi-static Loading Coefficients

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### Quasi-static Unloading Coefficients

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APPENDIX D

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APPENDIX D

IGOR Programming Summary
Data Analysis - summary and programming extracts

Data inputted to Igor Pro 6; programming language: modified C++

Vaulting data from 20 digitised markers (in centimetres), 3 load-cell forces for 69 vaults involving 8 participants
Analysed using 8 segment models

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<td>L knee</td>
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<td>L elbow</td>
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Forces: data from load cell in newtons; smoothing binomial level 150.

Energies: (all in joules)

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<tr>
<td>KErot_whole</td>
<td>rotational kinetic energy about centre of mass</td>
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<tr>
<td>PEelastic</td>
<td>elastic potential energy stored in compressed pole</td>
</tr>
<tr>
<td>PEGrav</td>
<td>gravitational potential energy of vaulter from centre of mass</td>
</tr>
<tr>
<td>TE</td>
<td>total energy</td>
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</table>
// consider a line with slope +m
// i.e. \( y = m \cdot x + b \)
// want pt in data with greatest b
// \( b = y - m \cdot x \) here \( y \) = force (F) and \( x \) = dx (displacement)
// plot: \( z = F - m \cdot dx \) and find max

**Function FindCornerPoint()**

Wave ppp=ppp,forceQ=forceQ,displacementQ=displacementQ
Wave forceD=forceD,displacementD=displacementD
Wave AllPoleFits=AllPoleFits
Variable/D p=0,poleN=ppp[10],nQ=numpnts(forceQ),nD=numpnts(forceD)
Variable/D m=J6,ff,dx,pp,inc=1 // m=ppp[6]
Variable/D turnQ=AllPoleFits[1][poleN],turnD=AllPoleFits[40][poleN]
// quasi-static data
Duplicate/O forceQ z_coef; z_coef=forceQ-m*displacementQ
WaveStats/R=[0,turnQ]/Q z_coef; pp=V_maxloc; ff=forceQ[pp]
dx=displacementQ[pp] // load
AllPoleFits[18][poleN]=m; AllPoleFits[13][poleN]=ff
AllPoleFits[14][poleN]=dx; AllPoleFits[12][poleN]=pp
Make/N=1/D/O maxQ_F,maxQ_DX; maxQ_F=ff; maxQ_DX=dx
WaveStats/R=[turnQ,nQ-1]/Q z_coef; pp=V_maxloc; ff=forceQ[pp]
dx=displacementQ[pp] // unload
AllPoleFits[31][poleN]=ff; AllPoleFits[32][poleN]=dx; AllPoleFits[30][poleN]=pp
Make/N=1/D/O maxQ_F,maxQ_DX; maxQ_F=ff; maxQ_DX=dx
// dynamic data
Duplicate/O forceD z_coef; z_coef=forceD-m*displacementD
WaveStats/R=[0,turnD]/Q z_coef; pp=V_maxloc; ff=forceD[pp]
dx=displacementD[pp] // load
AllPoleFits[52][poleN]=ff
AllPoleFits[53][poleN]=dx; AllPoleFits[51][poleN]=pp
Make/N=1/D/O maxD_F,maxD_DX; maxD_F=ff; maxD_DX=dx
WaveStats/R=[turnD,nD-1]/Q z_coef; pp=V_maxloc; ff=forceD[pp]
dx=displacementD[pp] // unload
AllPoleFits[72][poleN]=ff; AllPoleFits[73][poleN]=dx; AllPoleFits[71][poleN]=pp

End

// POLE ELASTIC ENERGY /////////
// USING COEFS ////////////// calls PoleEnergy(poleN,typ,meth,xs,xf)
// typ=0:load 1:unload  meth=0:QS 1:dyn

**Function PoleEnergyCoef()** // using coef fit to data for Full range (120-126)
// and up to % polelength (128-134)
// does not deal with drop in force on unload
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceQ=forceQ,displacementQ=displacementQ
Variable/D p=0,poleN=ppp[10],value,n=numpnts(forceQ),EL,EU,percent=ppp[13]
Variable/D nCol=Dimsize(AllPoleFits,1),turnPt=AllPoleFits[1][poleN],nL=turnPt,nU=n-turnPt
Variable/D poleLen=100*AllPoleFits[86][poleN],dL,dLmax,lastopt=ppp[83] // m -> cm
ppp[83]=1
// from QS fits:
FindMaxDisplacementQ(percent,poleLen,poleN)
dL=AllPoleFits[89][poleN]
WaveStats/Q displacementQ; dLmax=V_max
// QS Load full
value=PoleEnergy(poleN,0,0,0,dLmax); AllPoleFits[120][poleN]=value; EL=value
// QS Unload full
value=PoleEnergy(poleN,1,0,0,dLmax); AllPoleFits[121][poleN]=value; EU=value
EE=EL-EU; AllPoleFits[122][poleN]=100*EE/EL
// QS Load %
value=PoleEnergy(poleN,0,0,0,dL); AllPoleFits[128][poleN]=value; EL=value
// QS Unload %
value=PoleEnergy(poleN,1,0,0,dL); AllPoleFits[129][poleN]=value; EU=value
EE=EL-EU; AllPoleFits[130][poleN]=100*EE/EL
// from dyn fits:
FindMaxDisplacementD(percent,poleLen,poleN)
WaveStats/Q displacementD; dLmax=V_max
// dyn Load full
value=PoleEnergy(poleN,0,1,0,dLmax); AllPoleFits[124][poleN]=value; EL=value
// dyn Unload full
value=PoleEnergy(poleN,1,1,0,dLmax); AllPoleFits[125][poleN]=value; EU=value
EE=EL-EU; AllPoleFits[126][poleN]=100*EE/EL
// dyn Load %
value=PoleEnergy(poleN,0,1,0,dL); AllPoleFits[132][poleN]=value; EL=value
// dyn Unload %
value=PoleEnergy(poleN,1,1,0,dL); AllPoleFits[133][poleN]=value; EU=value
EE=EL-EU; AllPoleFits[134][poleN]=100*EE/EL
End

// USING FORCE DATA
Function FindMaxDisplacementQ(percent,poleLen,poleN)
Variable percent,poleLen,poleN
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceQ=forceQ,displacementQ=displacementQ
Variable/D fu,du,fL,dL,pU=-1,pL=-1,p=0,opt=ppp[9]
Variable/D
nL=AllPoleFits[1][poleN],nU=AllPoleFits[37][poleN],maxD=percent*poleLen/100,test
AllPoleFits[89][poleN]=maxD
do
  test=displacementQ[p]
  if(test>maxD)
    fL=(forceQ[p-1]+forceQ[p])/2; dL=(displacementQ[p-1]+displacementQ[p])/2
    pL=p-1
    break
  endif
  p+=1
while(p<nL)
p=nL
do
  test=displacementQ[p]
  if(test<maxD)
    fU=(forceQ[p-1]+forceQ[p])/2; dU=(displacementQ[p-1]+displacementQ[p])/2
    pU=p
    break
  endif
  p+=1
while(p<nU)
AllPoleFits[90][poleN]=pL; AllPoleFits[91][poleN]=fL; AllPoleFits[92][poleN]=dL;
AllPoleFits[93][poleN]=pU; AllPoleFits[94][poleN]=fU; AllPoleFits[95][poleN]=dU;
End
Function FindMaxDisplacementD(percent,poleLen,poleN)
Variable percent,poleLen,poleN
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceD=forceD,displacementD=displacementD
Variable/D fu,du,fL,dL,pU=-1,pL=-1,p=0,opt=ppp[9]
Variable/D
nL=AllPoleFits[40][poleN],nU=AllPoleFits[38][poleN],maxD=percent*poleLen/100,test
AllPoleFits[89][poleN]=maxD
do
  test=displacementD[p]
  if(test>maxD)
    fL=(forceD[p-1]+forceD[p])/2; dL=(displacementD[p-1]+displacementD[p])/2
    pL=p-1
  endif
  p+=1
while(p<nL)
p=nL
do
  test=displacementD[p]
  if(test<maxD)
    fU=(forceD[p-1]+forceD[p])/2; dU=(displacementD[p-1]+displacementD[p])/2
    pU=p
    break
  endif
  p+=1
while(p<nU)
AllPoleFits[90][poleN]=pL; AllPoleFits[91][poleN]=fL; AllPoleFits[92][poleN]=dL;
AllPoleFits[93][poleN]=pU; AllPoleFits[94][poleN]=fU; AllPoleFits[95][poleN]=dU;
End
break
p++=1
while(p<nL)
p=nL
do
test=displacementD[p]
if(test<maxD)
fU=(forceD[p-1]+forceD[p])/2; dU=(displacementD[p-1]+displacementD[p])/2
pU=p
break
endif
p++=1
while(p<nL)
AllPoleFits[96][poleN]=pL; AllPoleFits[97][poleN]=fL; AllPoleFits[98][poleN]=dL;
AllPoleFits[99][poleN]=pU; AllPoleFits[100][poleN]=fU; AllPoleFits[101][poleN]=dU;
End
Function PoleEnergyQ2() // integrate measured quasi-static data up to % polelength
// does not deal with drop in force on unload
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceQ=forceQ,displacementQ=displacementQ
//String fname,qname
Variable/D p=0,poleN=ppp[10],value,n=numpnts(forceQ),EL,EU,EE,percent=ppp[13]
Variable/D nCol=Dimsize(AllPoleFits,1),turnPt=AllPoleFits[1][poleN],nL=turnPt,nU=n-turnPt
Variable/D poleLen=100*AllPoleFits[86][poleN]  // m -> cm
FindMaxDisplacementQ(percent,poleLen,poleN)
Variable/D pL=AllPoleFits[90][poleN],fL=AllPoleFits[91][poleN],dL=AllPoleFits[92][poleN]
Variable/D pU=AllPoleFits[93][poleN],fU=AllPoleFits[94][poleN],dU=AllPoleFits[95][poleN]
if(pL<0 || pU<0)
Print "p < 0!!!?"
endif
// force in newtons, displacement in cm
Duplicate/R=[0,pL]/O forceQ fQL,energyQL  // loading
InsertPoints 0,1, fQL,energyQL
Duplicate/R=[0,pL+1]/O displacementQ dQL
InsertPoints 0,1, dQL
energyQL=NaN; energyQU=NaN; energyQ=NaN
Integrate/T fQL /X=dQL /D=energyQL
Integrate/T fQU /X=dQU /D=energyQU
Integrate/T fQ /X=dQ /D=energyQ
energyQL/=100; energyQU/=100; energyQ/=100  // from cm -> m to get joules
End
Function PoleEnergyQ() // integrate measured quasi-static data
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceQ=forceQ,displacementQ=displacementQ
Variable/D p=0,poleN=ppp[10],value,n=numpnts(forceQ),EL,EU,EE
Variable/D nCol=Dimsize(AllPoleFits,1),turnPt=AllPoleFits[1][poleN],nL=turnPt,nU=n-turnPt
// force in newtons, displacement in cm
Duplicate/R=[0,nL]/O forceQ fQL,energyQ // loading
Duplicate/R=[0,nL+1]/O displacementQ dQL
Duplicate/R=[nL,n-2]/O forceQ fQU,energyQU // unloading
Duplicate/R=[nL,n-1]/O displacementQ dQU
Duplicate/O displacementQ dQ // all in one
Duplicate/R=[0,n-2]/O forceQ fQ,energyQ
energyQL=NaN; energyQU=NaN; energyQ=NaN
Integrate/T fQL /X=dQL /D=energyQL
Integrate/T fQU /X=dQU /D=energyQU
Integrate/T fQ /X=dQ /D=energyQ
energyQL/=100; energyQU/=100; energyQ/=100 // from cm -> m to get joules
EL=energyQL[nL]; ppp[111]=EL; AllPoleFits[78][poleN]=EL
EU=energyQU[n-nL]; ppp[112]=EU; AllPoleFits[79][poleN]=EU
EE=energyQ[n-2]; ppp[113]=EE; AllPoleFits[80][poleN]=100*EE/EL
End

Function PoleEnergyD2() // integrate measured quasi-static data up to % polelength
// does not deal with drop in force on unload
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceD=forceD,displacementD=displacementD
Variable/D p=0,poleN=ppp[10],value,n=numpnts(forceD),EL,EU,EE,percent=ppp[13]
Variable/D nCol=Dimsize(AllPoleFits,1),turnPt=AllPoleFits[1][poleN],nl=turnPt,nU=n-turnPt
Variable/D poleLen=100*AllPoleFits[86][poleN] // m -> cm
FindMaxDisplacementD(percent,poleLen,poleN)
Variable/D pL=AllPoleFits[96][poleN],fL=AllPoleFits[97][poleN],dL=AllPoleFits[98][poleN]
Variable/D
pU=AllPoleFits[99][poleN],fU=AllPoleFits[100][poleN],dU=AllPoleFits[101][poleN]
if(pL<0 || pU<0)
  Print "p < 0!!!?"
endif
// force in newtons, displacement in cm
Duplicate/R=[0,pL]/O forceD fDL,energyDL // loading
InsertPoints pL+1,1, fDL,energyDL
fDL[pL+1]=fL
Duplicate/R=[0,pL+1]/O displacementD dDL
InsertPoints pl+2,1, dDL
dDL[pL+2]=dL
Duplicate/R=[pU,n-2]/O forceD fDU,energyDU // unloading
InsertPoints 0,1, fDU,energyDU
fDU[0]=fU
Duplicate/R=[pU,n-1]/O displacementD dDU
InsertPoints 0,1, dDU
dDU[0]=dU
Duplicate/O displacementD dD // all in one
Duplicate/R=[0,n-2]/O forceD fD,energyD
energyDL=NaN; energyDU=NaN; energyD=NaN
Integrate/T fDL /X=dDL /D=energyDL
Integrate/T fDU /X=dDU /D=energyDU
Integrate/T fD /X=dD /D=energyD
energyDL/=100; energyDU/=100; energyD/=100 // from cm -> m to get joules
EL=energyDL[nL+2]; ppp[111]=EL; AllPoleFits[107][poleN]=EL
EU=energyDU[n-pU]; ppp[112]=EU; AllPoleFits[108][poleN]=EU
EE=EL+EU; ppp[113]=EE; AllPoleFits[109][poleN]=100*EE/EL
End

Function PoleEnergyD() // integrate measured dynamic data
Wave ppp=ppp,AllPoleFits=AllPoleFits,AllPoleSDs=AllPoleSDs
Wave forceD=forceD,displacementD=displacementD
Variable/D p=0,poleN=ppp[10],value,n=numpnts(forceD),EL,EU,EE
Variable/D turnPt=AllPoleFits[40][poleN],restart=AllPoleFits[60][poleN],nL=turnPt,nU=n-restart
// force in newtons, displacement in cm
Duplicate/R=[0,nL]/O forceD fDL,energyDL // loading
Duplicate/R=[0,nL+1]/O displacementD dDL
Duplicate/R=[nL,n-2]/O forceD fDU,energyDU // unloading
Duplicate/R=[nL,n-1]/O displacementD dDU
Duplicate/O displacementD dD  // all in one
Duplicate/R=[0,n-2]/O forceD fD,energyD
energyDL=NaN; energyDU=NaN; energyD=NaN
Integrate/T fDL /X=dDL /D=energyDL
Integrate/T fDU /X=dDU /D=energyDU
Integrate/T fD /X=dD /D=energyD
energyDL/=100; energyDU/=100; energyD/=100 // from cm -> m to get joules
EL=energyDL[nL]; ppp[114]=EL; AllPoleFits[82][poleN]=EL
EU=energyDU[n-nL]; ppp[115]=EU; AllPoleFits[83][poleN]=EU
EE=energyD[n-2]; ppp[116]=EE; AllPoleFits[84][poleN]=100*EE/EL
End
Function FindParameters() // using corner Pts
// requires UpdateSelected() to have been called
// added pt where slope1 intersects slope2  2-Mar-15
Wave ppp=ppp,forceQ=forceQ,displacementQ=displacementQ
Wave forceD=forceD,displacementD=displacementD,selected_coefs=selected_coefs
Wave selected_SDs=selected_SDs,AllPoleIncs=AllPoleIncs
Variable/D p=0,ppp[n]=ppp[n],nQ=numpnts(forceQ),nD=numpnts(forceD)
Variable/D value,test,slop1,slop2,slop3,slop4,Finit=ppp[56],Flo=ppp[57],flag=0,p1,p2,p3,p4,p5
Variable/D turnQ=AllPoleFits[1][poleN],turnD=AllPoleFits[40][poleN],SD,flag2=0
Variable/D cornQL=AllPoleFits[12][poleN],cornDL=AllPoleFits[51][poleN],incL=1,incD=4,sP,eP
Variable/D cornQU=AllPoleFits[30][poleN],cornDU=AllPoleFits[71][poleN]
Variable/D sP=AllPoleIncs[0][poleN],eP=AllPoleIncs[1][poleN]
CurveFit/NTHR=0/TBOX=0/Q line  forceQ[sP,eP] /X=displacementQ
slop1=wn=coefficient[1]; ppp[30]=slop1
offQL=wn=coefficient[0]; ppp[38]=offQL
SD=wn=coefficient[1]; selected_SDs[10]=SD; selected_nPts[10]=eP-sP+1
SD=wn=coefficient[0]; selected_SDs[16]=SD; selected_nPts[16]=eP-sP+1
xx0=displacementQ[sP]
xx1=displacementQ[eP]
slopeQX[0]=xx0; slopeQX[1]=xx1;
slopeQY[0]=slop1*xx0; slopeQY[1]=slop1*xx1+offQL
// QS load low
sP=AllPoleIncs[2][poleN]; eP=AllPoleIncs[3][poleN]
CurveFit/NTHR=0/TBOX=0/Q line  forceQ[sP,eP] /X=displacementQ
slop2=wn=coefficient[1]; ppp[31]=slop2
intY1=wn=coefficient[0]; ppp[45]=intY1
SD=wn=coefficient[1]; selected_SDs[11]=SD; selected_nPts[11]=eP-sP+1
SD=wn=coefficient[0]; selected_SDs[17]=SD; selected_nPts[17]=eP-sP+1
xx2=displacementQ[sP]
XTurn=displacementQ[eP]
// QS unload low
sP=AllPoleIncs[4][poleN]; eP=AllPoleIncs[5][poleN]
CurveFit/NTHR=0/TBOX=0/Q line  forceQ[sP,eP] /X=displacementQ
slop3=wn=coefficient[1]; ppp[32]=slop3
intY2=wn=coefficient[0]; ppp[46]=intY2
SD=wn=coefficient[1]; selected_SDs[29]=SD; selected_nPts[29]=eP-sP+1
SD=wn=coefficient[0]; selected_SDs[35]=SD; selected_nPts[35]=eP-sP+1
XTurn=displacementQ[eP]
xx3=displacementQ[eP]
slopeQY[6]=intY2+slop3*xTurn; slopeQY[7]=intY2+slop3*xx3
// QS unload low
sP=AllPoleIncs[6][poleN]; eP=AllPoleIncs[7][poleN]
CurveFit/NTHR=0/TBOX=0/Q line forceQ[sP,eP] /X=displacementQ
slop4=w_coef[1]; ppp[33]=slop4
intY3=w_coef[0]; ppp[47]=intY3
SD=w_sigma[1]; selected_SDs[28]=SD; selected_nPts[28]=eP-sP+1
SD=w_sigma[0]; selected_SDs[34]=SD; selected_nPts[34]=eP-sP+1
xx4=displacementQ[sP]
xx5=displacementQ[eP]
// find where two lines intersect
// QS LOAD
x_corn=(intY1-offQL)/(slop1-slop2); ppp[121]=x_corn
F_corn=(slop1*intY1-offQL*slop2)/(slop1-slop2); ppp[120]=F_corn
// QS UNLOAD
x_corn=(intY2-intY3)/(slop4-slop3); ppp[123]=x_corn
F_corn=(slop4*intY2-intY3*slop3)/(slop4-slop3); ppp[122]=F_corn

/// DYNAMIC DATA //////////
// forceD=forceD,displacementD=displacementD,selected_coefs
// dynamic load low
sP=AllPoleIncs[8][poleN]; eP=AllPoleIncs[9][poleN]
CurveFit/NTHR=0/TBOX=0/Q line forceD[sP,eP] /X=displacementD
slop1=w_coef[1]; ppp[34]=slop1
offDL=w_coef[0]; ppp[39]=offDL
SD=w_sigma[1]; selected_SDs[49]=SD; selected_nPts[49]=eP-sP+1
SD=w_sigma[0]; selected_SDs[55]=SD; selected_nPts[55]=eP-sP+1
xx0=displacementD[sP]
xx1=displacementD[eP]
// dynamic load high
sP=AllPoleIncs[10][poleN]; eP=AllPoleIncs[11][poleN]
CurveFit/NTHR=0/TBOX=0/Q line forceD[sP,eP] /X=displacementD
slop2=w_coef[1]; ppp[35]=slop2
intY1=w_coef[0]; ppp[52]=intY1
SD=w_sigma[1]; selected_SDs[50]=SD; selected_nPts[50]=eP-sP+1
SD=w_sigma[0]; selected_SDs[56]=SD; selected_nPts[56]=eP-sP+1
xx2=displacementD[sP]
// dynamic unload high
xTurn=displacementD[turnD]
sP=AllPoleIncs[12][poleN]; eP=AllPoleIncs[13][poleN]
CurveFit/NTHR=0/TBOX=0/Q line forceD[sP,eP] /X=displacementD
slop3=w_coef[1]; ppp[36]=slop3
intY2=w_coef[0]; ppp[53]=intY2
SD=w_sigma[1]; selected_SDs[70]=SD; selected_nPts[70]=eP-sP+1
SD=w_sigma[0]; selected_SDs[76]=SD; selected_nPts[76]=eP-sP+1
xx3=displacementD[eP]
// dynamic unload low
sP=AllPoleIncs[14][poleN]; eP=AllPoleIncs[15][poleN]
CurveFit/NTHR=0/TBOX=0/Q line forceD[sP,eP] /X=displacementD
slop4=w_coef[1]; ppp[37]=slop4
intY3=w_coef[0]; ppp[54]=intY3
SD=w_sigma[1]; selected_SDs[69]=SD; selected_nPts[69]=eP-sP+1
SD=w_sigma[0]; selected_SDs[75]=SD; selected_nPts[75]=eP-sP+1
xx4=displacementD[sP]
xx5=displacementD[eP]
Make/N=11/D/O slopeDX,slopeDY; slopeDY=NaN
slopeDX[0]=xx0; slopeDX[1]=xx1; slopeDX[3]=xx2; slopeDX[4]=xTurn
slopeDY[0]=offDL+slop1*xx0; slopeDY[1]=offDL+slop1*xx1
// find where two lines intersect
// dyn LOAD
x_corn=(intY1-offDL)/(slop1-slop2); ppp[125]=x_corn
F_corn=(slop1*intY1-offDL*slop2)/(slop1-slop2); ppp[124]=F_corn
// dyn UNLOAD
x_corn=(intY2-intY3)/(slop4-slop3); ppp[127]=x_corn
F_corn=(slop4*intY2-intY3*slop3)/(slop4-slop3); ppp[126]=F_corn
End

////////////////////////////////////////////////////////////////////
// UNITS:
// since digitisation is for x,y,z in cm we need to /100 to get metres
// and joules in results
// for KE: (1/2)mv^2 => KE (in joules) = KE(in cm*cm^2) * 10^-6

// POLE FIT FUNCTION //////////////////////////////////////////////////
// from fit to QS and dynamic data force versus displacement
// force(x) = a + b*(x-xo)-c/(x-xo+d)+h*((x-xo)/f)^g
// pole_energy(xs,xf) is the integral of force(x) from x=xs to x=xf
//
// pole_energy(xs,xf) = a*(xf-xs) + (1/2)*b*(xf^2-xs^2) + b*xo*(xf-xs)
// -c*ln((f+d+xf-xo)/(f+d-xo+xs))
// +((h^f(1+g))^-((xf-xo)^g(1+g)) - (xs-xo)^g(1+g))

Function PoleForce(x,typ)
Variable/D x,typ
Wave ppp=ppp
Variable/D poleN=ppp[10],meth=ppp[12],xs,xf
Variable/D value,test,a,b,c,d,f,g,h,xo
test=SelectPoleCoefs()
if(typ==0) // load
  if(meth==0) // load, QS
    value=selected_coefs[2]; ppp[20]=value  // a
    value=selected_coefs[3]; ppp[21]=value  // b
    value=selected_coefs[4]; ppp[22]=value  // c
    value=selected_coefs[5]; ppp[23]=value  // d
    value=selected_coefs[6]; ppp[24]=value  // f
    value=selected_coefs[7]; ppp[25]=value  // g
    value=selected_coefs[8]; ppp[26]=value  // h
    value=selected_coefs[9]; ppp[27]=value  // xo
  else  // load, dyn
    value=selected_coefs[41]; ppp[20]=value  // a
    value=selected_coefs[42]; ppp[21]=value  // b
    value=selected_coefs[43]; ppp[22]=value  // c
    value=selected_coefs[44]; ppp[23]=value  // d
    value=selected_coefs[45]; ppp[24]=value  // f
    value=selected_coefs[46]; ppp[25]=value  // g
    value=selected_coefs[47]; ppp[26]=value  // h
    value=selected_coefs[48]; ppp[27]=value  // xo
  endif
else
  if(meth==0) // unload, QS
    value=selected_coefs[20]; ppp[20]=value  // a
    value=selected_coefs[21]; ppp[21]=value  // b
    value=selected_coefs[22]; ppp[22]=value  // c
    value=selected_coefs[23]; ppp[23]=value  // d
    value=selected_coefs[24]; ppp[24]=value  // f
    value=selected_coefs[25]; ppp[25]=value  // g
    value=selected_coefs[26]; ppp[26]=value  // h
    value=selected_coefs[27]; ppp[27]=value  // xo
  endif
else  // unload, dyn
    value=selected_coefs[61]; ppp[20]=value  // a
    value=selected_coefs[62]; ppp[21]=value  // b
    value=selected_coefs[63]; ppp[22]=value  // c
    value=selected_coefs[64]; ppp[23]=value  // d
    value=selected_coefs[65]; ppp[24]=value  // f
    value=selected_coefs[66]; ppp[25]=value  // g
    value=selected_coefs[67]; ppp[26]=value  // h
    value=selected_coefs[68]; ppp[27]=value  // xo
endif
a=ppp[20]; b=ppp[21]; c=ppp[22]; d=ppp[23]; f=ppp[24]; g=ppp[25]; h=ppp[26]; xo=ppp[27]
a=c/d
test=numtype(h)
if(test==2)  // i.e. NaN
    h=1
endif
test=numtype(xo)
if(test==2)  // i.e. NaN
    xo=0
endif
if(xs<=xo)
    xs=xo
endif
Variable/D aa,bb,cc,dd
//
value=a+b*(x-xo)-c/((x-xo)+d)+h*((x-xo)/f)^g
//
//Print x,a,b,c,d,h,f,g,xo,value
Return(value)
End
///// POLE BENDING & ENERGY ///////
// sync between force data and poletop position
Function PoleEnergy(poleN,typ,meth,xs,xf)
// calculate integral of fitted pole F vs x function from x=xs to x=xf
Variable/D poleN,typ,meth,xs,xf
Wave ppp=ppp
ppp[10]=poleN
Variable/D value,test,a,b,c,d,f,g,h,xo,opt=ppp[83],factor=1,dum
if(opt==0)
    typ=0   // uses same load curve for unload
endif
test=SelectPoleCoefs()
if(typ==0)  // load
    if(meth==0)  // load, QS
        value=selected_coefs[2]; ppp[20]=value  // a
        value=selected_coefs[3]; ppp[21]=value  // b
        value=selected_coefs[4]; ppp[22]=value  // c
        value=selected_coefs[5]; ppp[23]=value  // d
        value=selected_coefs[6]; ppp[24]=value  // f
        value=selected_coefs[7]; ppp[25]=value  // g
        value=selected_coefs[8]; ppp[26]=value  // h
        value=selected_coefs[9]; ppp[27]=value  // xo
    else  // load, dyn
        value=selected_coefs[41]; ppp[20]=value  // a
        value=selected_coefs[42]; ppp[21]=value  // b
        value=selected_coefs[43]; ppp[22]=value  // c
        value=selected_coefs[44]; ppp[23]=value  // d
        value=selected_coefs[45]; ppp[24]=value  // f
        value=selected_coefs[46]; ppp[25]=value  // g
        value=selected_coefs[47]; ppp[26]=value  // h
endif

value=selected_coefs[48]; ppp[27]=value // xo

endif

else
    // unload
    if(meth==0) // unload, QS
        value=selected_coefs[20]; ppp[20]=value // a
        value=selected_coefs[21]; ppp[21]=value // b
        value=selected_coefs[22]; ppp[22]=value // c
        value=selected_coefs[23]; ppp[23]=value // d
        value=selected_coefs[24]; ppp[24]=value // f
        value=selected_coefs[25]; ppp[25]=value // g
        value=selected_coefs[26]; ppp[26]=value // h
        value=selected_coefs[27]; ppp[27]=value // xo
    endif

    if(meth==1) // unload, dyn
        value=selected_coefs[61]; ppp[20]=value // a
        value=selected_coefs[62]; ppp[21]=value // b
        value=selected_coefs[63]; ppp[22]=value // c
        value=selected_coefs[64]; ppp[23]=value // d
        value=selected_coefs[65]; ppp[24]=value // f
        value=selected_coefs[66]; ppp[25]=value // g
        value=selected_coefs[67]; ppp[26]=value // h
        value=selected_coefs[68]; ppp[27]=value // xo
    endif
endif

a=ppp[20]; b=ppp[21]; c=ppp[22]; d=ppp[23]; f=ppp[24]; g=ppp[25]; h=ppp[26]; xo=ppp[27]
a=c/d

test=numtype(h)
if(test==2) // i.e. NaN
    h=1
endif

test=numtype(xo)
if(test==2) // i.e. NaN
    xo=0
endif

if(xs<=xo)
    xs=xo
endif

Variable/D aa, bb, cc, dd

value=a*(xf-xs) + (1/2)*b*(xf^2-xs^2) - b*xo*(xf-xs)
value+=c*ln((d+xf-xo)/(d-xo+xs))
value+=(f*h*(1+g))/(1+(1+g))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))
value=-(c*ln((d+xf-xo)/(d-xo+xs))

End

// Function FindMaxForces() // includes impulse calculation

Wave ppp=ppp, forceX=forceX, forceY=forceY, forceZ=forceZ, force_mag=force_mag
Wave wave_result=wave_result, contact_pF=contact_pF, contact_lastpF=contact_lastpF
Wave wave=wave, j_MPB_frame=j_MPB_frame, j_PP_frame=j_PP_frame

Variable/D n=numpnts(force_mag), maxvalue, maxloc, cod=ppp[99], p1=contact_pF[cod]

Variable/D p2=contact_lastpF[cod], eP=p2-p1, int, opt=ppp[5]

Variable/D p3, p_PP=j_PP_frame[cod], pMPB=j_MPB_frame[cod], p4=p1+10*(pMPB-p_PP)

Duplicate/O/R=[p1, p2] ms dumms; dumms/=500 // convert to seconds

// X component

WaveStats/Q forceX, maxvalue=V_max, maxloc=V_maxloc; p3=maxloc

force_result[cod][0]=maxvalue; force_result[cod][4]=maxloc-p1)*0.002

Duplicate/O/R=[p1, p2] forceX dumForce

Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]

force_result[cod][8]=int

188
Duplicate/O/R=[p1,p3] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p3] forceX dumForce; eP=p3-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][12]=int
Duplicate/O/R=[p3,p2] ms dumms; dumms/=500 // convert to seconds
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][15]=int
Duplicate/O/R=[p1,p4] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p4] forceX dumForce; eP=p4-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][18]=int
Duplicate/O/R=[p4,p2] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p4,p2] forceX dumForce; eP=p2-p4
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][21]=int

// Y component
WaveStats/Q forceY; maxvalue=V_max; maxloc=V_maxloc
force_results[cod][1]=maxvalue; force_results[cod][5]=(maxloc-p1)*0.002
Duplicate/O/R=[p1,p2] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p2] forceY dumForce; eP=p2-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][9]=int

// Z component
WaveStats/Q forceZ; maxvalue=V_min; maxloc=V_minloc; p3=maxloc
force_results[cod][2]=maxvalue; force_results[cod][6]=(maxloc-p1)*0.002
Duplicate/O/R=[p1,p2] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p2] forceZ dumForce; eP=p2-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][10]=int
Duplicate/O/R=[p1,p3] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p3] forceX dumForce; eP=p3-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][13]=int
Duplicate/O/R=[p3,p2] ms dumms; dumms/=500 // convert to seconds
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][16]=int
Duplicate/O/R=[p1,p4] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p4] forceX dumForce; eP=p4-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][19]=int
Duplicate/O/R=[p4,p2] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p4,p2] forceX dumForce; eP=p2-p4
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][22]=int

// magnitude
WaveStats/Q force_mag; maxvalue=V_max; maxloc=V_maxloc; p3=maxloc
force_results[cod][3]=maxvalue; force_results[cod][7]=(maxloc-p1)*0.002
Duplicate/O/R=[p1,p2] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p2] force_mag dumForce; eP=p2-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][11]=int
Duplicate/O/R=[p1,p3] ms dumms; dumms/=500 // convert to seconds
Duplicate/O/R=[p1,p3] forceX dumForce; eP=p3-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][14]=int
Duplicate/O/R=[p3,p2] ms dumms; dumms/=500 // convert to seconds
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][17]=int
Duplicate/O/R=[p1,p4] ms dumms; dumms/=500       // convert to seconds
Duplicate/O/R=[p1,p4] forceX dumForce; eP=p4-p1
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][20]=int
Duplicate/O/R=[p4,p2] ms dumms; dumms/=500       // convert to seconds
Duplicate/O/R=[p4,p2] forceX dumForce; eP=p2-p3
Integrate/METH=1 dumForce/X=dumms/D=dumImpulse; int=dumImpulse[eP]
force_results[cod][23]=int

End

 ////////// Normalised force for single jumps //////////

Function MakeNormalisedForceSingle()
Wave/T p_name=p_name
Wave ppp=ppp,force_loaded=force_loaded,j_frames=j_frames
Wave force_mag=force_mag,contact_pF=contact_pF,contact_lastpF=contact_lastpF
Wave contact_frame=contact_frame,jump_codes=jump_codes
Variable/D
p=0,Nave=numpnts(selected),p1,p2,p3,n=ppp[60],k,m,framF=2499,lastnamep=ppp[99]
Variable/D fnum,fram,loaded,opt=ppp[19],test,conF,popt=ppp[5],conF1,conF2,conF3
String wname=p_name[58],jname
Wave w=$wname
ppp[19]=0  // use force data
Make/N=(2*n+1)/D/O dum1D; dum1D=NaN       // 2*n+1 = 101 for n = 50
fnum=ppp[99]; jname=jump_codes[fnum]; p_name[99]=jname
m=vaulter_m[fnum]; ppp[6]=m
conF=contact_frame[fnum]; ppp[90]=conF
loaded=force_loaded[fnum]
fram=j_frames[fnum]; ppp[101]=fram
RecallDataSet()
DoUpdate
if(loaded==1) // use force data
RecallFromStored()
UpdateForceGraph()
SmoothForceData()
ProcessData()
else
//Print fnum,"force data missing!!!"
ppp[19]=1
ProcessData()  // uses coefs for missing force data (i.e. fnum=56)
ppp[19]=0
endif
p1=j_PP_frame[fnum]; p2=j_MPB_frame[fnum]; p3=j_PS_frame[fnum]
conF1=contact_pF[fnum]; conF3=contact_lastpF[fnum]
conF2=round(conF1+((p2-p1)/(p3-p1))*(conF3-conF1))
DoUpdate
TimeNormalisedForceSingle(w,dum2D,conF1,conF2,conF3,n)
ppp[19]=opt    // reset to what was there before
RestorePrevious(lastfnum)
End

 ////////// Normalised force for grouped jumps //////////

Function MakeNormalisedForce()  // as determined by options on normalised energy graph
Wave/T p_name=p_name       // ppp[62 to 66]
Wave ppp=ppp,force_loaded=force_loaded,j_frames=j_frames
Wave force_mag=force_mag,contact_pF=contact_pF,contact_lastpF=contact_lastpF
Wave contact_frame=contact_frame,jump_codes=jump_codes
ExtractSelected()
Variable/D
p=0,Nave=numpnts(selected),p1,p2,p3,n=ppp[60],k,m,framF=2499,lastnamep=ppp[99]
Variable/D fnum,fram,loaded,opt=ppp[19],test,conF,popt=ppp[5],conF1,conF2,conF3
String wname=p_name[58],jname
Wave w=$wname
ppp[59]=Nave

190
ppp[19]=0 // use force data
if(Nave>1)
    Make/N=(2*n+1,Nave)/D/O dum2D; dum2D=NaN // 2*n+1 = 101 for n = 50
    do
        fnum=selected[p]; jname=jump_codes[fnum]; p_name[99]=jname
        ppp[99]=fnum
        m=vaulter_m[fnum]; ppp[6]=m
        conF=contact_frame[fnum]; ppp[90]=conF
        loaded=force_loaded[fnum]
        fram=j_frames[fnum]; ppp[101]=fram
        RecallDataSet()
        DoUpdate
        if(loaded==1) // use force data
            RecallFromStored()
            UpdateForceGraph()
            SmoothForceData()
        else
            //Print fnum,"force data missing!!!"
            ppp[19]=1
            ProcessData() // uses coefs for missing force data (i.e. fnum=56)
            ppp[19]=0
        endif
        p1=j_PP_frame[fnum]; p2=j_MPB_frame[fnum]; p3=j_PS_frame[fnum]
        conF1=contact_pF[fnum]; conF3=contact_lastpF[fnum]
        conF2=round(conF1+((p2-p1)/(p3-p1))*(conF3-conF1))
        // conF1: PP  conF2: MPB  conF3: PS
        DoUpdate
        TimeNormalisedForce(w,dum2D,conF1,conF2,conF3,n,p,Nave)
        // transfers time-adjusted force to dum2D[[p]]
        p+=1
        while(p<Nave)
            FindMeanFSD()
        endif
    ppp[19]=opt // reset to what was there before
    RestorePrevious(lastfnum)
End

Function TimeNormalisedForceSingle(w1,w2,p1,p2,p3,n)
// add w1 between frames p1 and p2 into n point 1D wave w2
// n here is # pts on each side of MPB  (i.e. 50)
Wave w1,w2
Variable/D p1,p2,p3,n
Wave ppp=ppp
Variable/D m=ppp[6],dx,p=0,value,pts,popt=ppp[5],cod=ppp[99]
InterpolateWave(w1,p1,p2,n+1)
pts=numpnts(intdumY)
Duplicate/O intdumY intdum1
InterpolateWave(w1,p2,p3,n+1)
Duplicate/O intdumY intdum2
Make/N=(2*n+1)/D/O normF_Xaxis,normForce
    do
        normF_Xaxis[p]=p1+p*(p2-p1)/(n)
        value=normF_Xaxis[p]; normForce[p]=value
        p+=1
    while(p<n)
    p=n
    do
        normF_Xaxis[p]=p2+(p-n)*(p3-p2)/(n)
        value=normF_Xaxis[p]; normForce[p]=value
        p+=1
    while(p<2*n+1)
value=intdum2[n]; normForce[2*n-1]=value
Duplicate/O normForce w2
End

Function TimeNormalisedForce(w1,w2,p1,p2,p3,n,k,Nave)
  // add w1 between frames p1 and p2 into n by Nave 2D wave w2
  // where w1 is the k-th file of total Nave
  // n here is # pts on each side of MPB  (i.e. 50)
Wave w1,w2
Variable/D p1,p2,p3,n,k,Nave
Wave ppp=ppp
Variable/D m=ppp[6],dx,p=0,value,pts,popt=ppp[5],cod=ppp[99]
InterpolateWave(w1,p1,p2,n+1)
pts=numpnts(intdumY)
Duplicate/O intdumY intdum1
InterpolateWave(w1,p2,p3,n+1)
Duplicate/O intdumY intdum2
Make/N=(2*n+1)/D/O normF_Xaxis,normForce
do
  normF_Xaxis[p]=p1+p*(p2-p1)/(n)
  value=intdum1[p]; normForce[p]=value
  p+=1
while(p<n)
p=n
do
  normF_Xaxis[p]=p2+(p-n)*(p3-p2)/(n)
  value=intdum2[p-n]; normForce[p]=value
  p+=1
while(p<2*n+1)
value=intdum2[n]; normForce[2*n-1]=value
// to make a wave intdumX and intdumY
CopyWave2Column2D(normForce,w2,k)
End

Function FindMeanFSD()
Wave dum2D=dum2D,normForce=normForce
Variable/D n=ppp[60],p=0,Nave=DimSize(dum2D,1)
Make/N=(2*n+1)/D/O normFSD; normFSD=nan
Make/N=(Nave)/D/O dumdum; dumdum=nan
Duplicate/O normForce FUSD,FLSD
do
  CopyRow2D2wave(dum2D,p,dumdum)
  WaveStats/Q dumdum
  normForce[p]=V_avg; normFSD[p]=V_sdev
  p+=1
while(p<2*n+1)
FUSD=normForce+normFSD
FLSD=normForce-normFSD
SetScale/I x -100,100,"", normForce,FUSD,FLSD
End

////////////////////////////////////////////////////////////////////
// sync between force data and poletop position
Function FindContactPointF() // to find contact_lastpF
Wave ppp=ppp,force_mag=force_mag,contact_pF=contact_pF
Wave force_loaded=force_loaded,contact_lastpF=contact_lastpF
Wave force_mag_DIF=force_mag_DIF
Wave/T jump_codes=jump_codes,p_name=p_name
Variable/D p=0,q=0,nF,n=numpnts(jump_codes),conf,zero,Fdiff
Variable/D thresh=ppp[91],thresh2=ppp[97],test,loaded,flag=0
String fname,jname
do
  jname=jump_codes[q]
  fname="F"+jname[1,4]

p_name[94]=fname; p_name[99]=jname
ppp[99]=q
loaded=force_loaded[q]
flag=0
if(loaded==1)
    SmoothForceData()
    WaveStats/R=[0,50]/Q force_mag; zero=V_avg
    force_mag.=zero
    p=0; nF=numpnts(force_mag)
    do
        test=force_mag[p]
        if(flag==0)  // looking for first contact
            if(test>thresh)
                contact_pF[q]=p-1; flag=1
            endif
        endif
        if(flag==1)  // get past initial stage
            if(test>500)
                flag=2
            endif
        endif
        if(flag==2)  // looking for last contact
            Fdiff=force_mag_DIF[p]
            if(Fdiff>0)
                if(test<thresh2)
                    contact_lastpF[q]=p-1
                    break
                endif
            endif
        endif
        p+=1
    while(p<nF)
    q+=1
while(q<n)
End

Function MakeNormalisedForces()
    Wave/T p_name=p_name
    p_name[58]="force_mag"
    MakeNormalisedForce()
    Duplicate/O normForce norm_mag
    Duplicate/O FUSD norm_magU
    Duplicate/O FLSD norm_magL
    p_name[58]="forceX"
    MakeNormalisedForce()
    Duplicate/O normForce norm_X
    Duplicate/O FUSD norm_XU
    Duplicate/O FLSD norm_XL
    p_name[58]="forceY"
    MakeNormalisedForce()
    Duplicate/O normForce norm_Y
    Duplicate/O FUSD norm_YU
    Duplicate/O FLSD norm_YL
    p_name[58]="forceZ"
    MakeNormalisedForce()
    Duplicate/O normForce norm_Z
    Duplicate/O FUSD norm_ZU
    Duplicate/O FLSD norm_ZL
End

Function TimeNormalisedEnergySingle(w1,w2,p1,p2,p3,n)
    // convert w1 between frames p1 and p2 into n pt 1D wave w2
// n here is # pts on each side of MPB (i.e. 50)
Wave w1, w2
Variable/D p1, p2, p3, n
Wave ppp = ppp
Variable/D m = ppp[6], dx, p = 0, value, pts, popt = ppp[5], cod = ppp[99]
InterpolateWave(w1, p1, p2, n+1)
pts = numpts(intdumY)
Duplicate/O intdumY intdum1
InterpolateWave(w1, p2, p3, n+1)
Duplicate/O intdumY intdum2
Make/N = (2*n+1)/D/O norm_Xaxis, normEnergy
do
    norm_Xaxis[p] = p1 + p*(p2-p1)/(n)
    value = intdum1[p]; normEnergy[p] = value
p += 1
while(p < n)
p = n
do
    norm_Xaxis[p] = p2 + (p-n)*(p3-p2)/(n)
    value = intdum2[p-n]; normEnergy[p] = value
p += 1
while(p < 2*n+1)
value = intdum2[n]; normEnergy[2*n-1] = value
// to make a wave intdumX and intdumY
if(popt == 1)
    WaveStats/Q normEnergy
    Print cod, V_max, V_min, "J", m, "kg"
endif
normEnergy /= m // for J/kg
if(popt == 1)
    WaveStats/Q normEnergy
    Print cod, V_max, V_min, "J/kg"
endif
intdum1 /= m; intdum2 /= m
Duplicate/O normEnergy w2
End

Function MakeNormalisedEnergySingle()
Wave/T p_name = p_name
Wave ppp = ppp, force_loaded = force_loaded, j_frames = j_frames
Wave contact_frame = contact_frame, jump_codes = jump_codes
Wave NormalisedEnergy = NormalisedEnergy
Variable/D p = 0, Nave = numpts(selected), p1, p2, p3, n = ppp[60], k, m, lastfnum = ppp[99]
Variable/D fnum, fram, loaded, opt = ppp[19], test, conF, popt = ppp[5]
String wname = p_name[61], jname // this determines which energy
Wave w = $wname
Make/N = (2*n+1)/D/O dum1D; dum1D = NaN // 2*n+1 = 101 for n = 50
fnum = ppp[99]; jname = jump_codes[fnum]; p_name[99] = jname
m = vaulter_m[fnum]; ppp[6] = m
conF = contact_frame[fnum]; ppp[90] = conF
loaded = force_loaded[fnum]
fram = j_frames[fnum]; ppp[101] = fram
RecallDataSet()
DoUpdate
if(opt == 0)
    if(loaded == 1) // use force data
        RecallFromStored()
        UpdateForceGraph()
        SmoothForceData()
        ProcessData()
    else
        Print fnum,"force data missing!!!!"
endif
    if(popt == 1)
        WaveStats/Q normEnergy
        Print cod, V_max, V_min, "J/kg"
    endif
endif
intdum1 /= m; intdum2 /= m
Duplicate/O normEnergy w2
End
ppp[19]=1
ProcessData()  // uses coefs for missing force data (i.e. fnum=56)
ppp[19]=0
endif
else  // use coef data
    ProcessData()
endif

p1=j KEinit_frame[fnum]; p2=j MPB_frame[fnum]; p3=j hmax_frame[fnum]
DoUpdate
TimeNormalisedEnergySingle(w,dum1D,p1,p2,p3,n)
// transfers time-adjusted energy w to dum1D

/////////////////////////////// GROUPED BY OPTIONS //////////////////////////////

Function MakeNormalisedEnergy()  // as determined by options on graph
    Wave/T p_name=p_name  // ppp[62 to 66]
    Wave ppp=ppp,force_loaded=force_loaded,j frames=j frames
    Wave contact_frame=contact_frame,jump_codes=j jump_codes
    ExtractSelected()
    Variable/D p=0,Nave=numpnts(selected),p1,p2,p3,n=ppp[60],k,m,lastfnum=ppp[99]
    Variable/D fnum,fram,loaded,opt=ppp[19],test,conF,popt=ppp[5]
    String wname=p_name[61],jname  // this determines which energy
    Wave w=$wname
    ppp[59]=Nave
    String/G strJ59="Z36"+num2str(Nave)
    DoWindow/HIDE=? g selected
    test=V_flag
    if(test==1)
        DoWindow/F g selected
        TextBox/C/N=text0/F=0/A=MC strJ59
    endif
    if(Nave>1)
        Make/N=(2*n+1,Nave)/D/O dum2D; dum2D=NaN  // 2*n+1 = 101 for n = 50
        do
            fnum=selected[p]; jname=jump_codes[fnum]; p_name[99]=jname
            ppp[99]=fnum
            m=vaulter_m[fnum]; ppp[6]=m
            conF=contact_frame[fnum]; ppp[90]=conF
            loaded=force_loaded[fnum]
            fram=j frames[fnum]; ppp[101]=fram
            RecallDataSet()
            DoUpdate
            if(opt==0)
            if(loaded==1)  // use force data
                RecallFromStored()
                UpdateForceGraph()
                SmoothForceData()
                ProcessData()
            else
                Print fnum,"force data missing!!!"
                ppp[19]=1
                ProcessData()  // uses coefs for missing force data (i.e. fnum=56)
            endif
            else  // use coef data
                ProcessData()
            endif
            p1=j KEinit_frame[fnum]; p2=j MPB_frame[fnum];
            p3=j hmax_frame[fnum]
            DoUpdate
            TimeNormalisedEnergy(w,dum2D,p1,p2,p3,n,p,Nave)
 transfers time-adjusted energy w to dum2D[][p]
  p+=1
  while(p<Nave)
    FindMeanSD()
  endif
  RestorePrevious(lastfnum) // restore previous data file
End

Function FindMeanSD()
  Wave dum2D=dum2D, normEnergy=normEnergy
  Variable/D n=ppp[60],p=0, Nave=DimSize(dum2D,1)
  Make/N=(2*n+1)/D/O normSD; normSD=nan
  Make/N=(Nave)/D/O dumdum; dumdum=nan
  Duplicate/O normEnergy USD,LSD
  do
    CopyRow2D2wave(dum2D,p,dumdum)
    WaveStats/Q dumdum
    normEnergy[p]=V_avg; normSD[p]=V_sdev
    p+=1
  while(p<2*n+1)
  USD=normEnergy+normSD
  LSD=normEnergy-normSD
  SetScale/I x -100,100,"", normEnergy,USD,LSD
End

Function TimeNormalisedEnergy(w1,w2,p1,p2,p3,n,k,Nave)
  // add w1 between frames p1 and p2 into n by Nave 2D wave w2
  // where w1 is the k-th file of total Nave
  // n here is # pts on each side of MPB  (i.e. 50)
  Wave w1,w2
  Variable/D p1,p2,p3,n,k,Nave
  Wave ppp=ppp
  Variable/D m=ppp[6],dx,p=0,value,pts,popt=ppp[5],cod=ppp[99]
  InterpolateWave(w1,p1,p2,n+1)
  pts=numpnts(intdumY)
  Duplicate/O intdumY intdum1
  InterpolateWave(w1,p2,p3,n+1)
  Duplicate/O intdumY intdum2
  Make/N=(2*n+1)/D/O norm_Xaxis,normEnergy
  do
    norm_Xaxis[p]=p1+p*(p2-p1)/(n)
    value=intdum1[p]; normEnergy[p]=value
    p+=1
  while(p<n)
  p=n
  do
    norm_Xaxis[p]=p2+(p-n)*(p3-p2)/(n)
    value=intdum2[p-n]; normEnergy[p]=value
    p+=1
  while(p<2*n+1)
  value=intdum2[n]; normEnergy[2*n-1]=value
  // to make a wave intdumX and intdumY
  normEnergy/=m // for J/kg
  intdum1/=m; intdum2/=m
  CopyWave2Column2D(normEnergy,w2,k)
  // copies 1D wave w1[] to w2[][column]
End

Function InterpolateWave(w,p1,p2,n)
  // to make a wave intdumX and intdumY
  Wave w
  Variable p1,p2,n
  Duplicate/O w intdumX; intdumX=x  // this is the frame number for w
  Make/N=(n)/D/O intdumY
SetScale/I x p1,p2,"", intdumY
intdumY=interp(x, intdumX, w)
End

////////////////////////////////////////////////////////////////////

// UNITS:
// since digitisation is for x,y,z in cm we need to /100 to get metres
// and joules in results
// for KE: (1/2)mv^2 => KE (in joules) = KE (in cm*cm^2) * 10^-6

POLE FIT FUNCTION

// from fit to QS and dynamic data force versus displacement
// force(x) = a + b*(x-xo)-c/(x-xo+d)+h*((x-xo)/f)^g
// pole_energy(xs,xf) is the integral of force(x) from x=xs to x=xf

// pole_energy(xs,xf) = a*(xf-xs) + (1/2)*b*(xf^2-xs^2) + b*xo*(xf-xs)
//   -c*ln((d+xf-xo)/(d-xo+xs))
//   +(f*h/((1+g)*f^(1+g)))*((xf-xo)^(1+g) - (xs-xo)^(1+g))

////////////////////////////////////////////////////////////////////

Function FindInitialKE()

// determines midpoint of last stride
// using 3 thresholds for ground contact
// outputs: p4 : ppp[56] : frame number

Wave ppp=ppp,Y1=Y1,Y9=Y9,time_axis=time_axis
Variable/D p=0,n=ppp[101],threshLF=ppp[51],LF,RF,flag1=0,flag2=0,p1,p2,t1,t2
Variable/D RF1,LF1,p3,t3,flag3=0,LF2,threshRF=ppp[53],thresh2=ppp[54]
Make/N=1/D/O LF1X,LF1Y,RF1X,RF1Y,LF2X,LF2Y

do
    LF=Y1[p]; RF=Y9[p]
    if(flag1==0)
        if(LF<threshLF)
            ppp[50]=p; flag1=1; p1=p; LF1=LF
            t1=time_axis[p1]
        endif
    endif
    if(flag1==1 && flag2==0)
        if(RF<threshRF)
            ppp[52]=p; flag2=1; p2=p; RF1=RF
            t2=time_axis[p2]
        endif
    endif
    p+=1
while(p<n)
    LF1X=t1; LF1Y=LF1
    RF1X=t2; RF1Y=RF1
    p=p1
    do
        LF=Y1[p]
        if(flag3==0)
            if(LF>thresh2+LF1)
                p3=p-1; LF2=Y1[p-1]
                t3=time_axis[p-1]; flag3=1
            endif
        endif
        p+=1
while(p<p2)
    LF2X=t3; LF2Y=LF2
    Wave KEtrans=KEtrans
    Variable/D test=p2-p3-1,p4,t4,KEinit=-1
    if(mod(test,2)==0)  // even num of pts between p2 and p3
        if(LF2Y>RF1Y)
            // ...
198

```
p4=floor((p2+p3)/2); t4=time_axis[p4]
KEinit=KEtrans[p4]
else
    p4=ceil((p2+p3)/2); t4=time_axis[p4]
    KEinit=KEtrans[p4]
endif
else  // odd
    p4=(p2+p3)/2
    KEinit=KEtrans[p4]
    t4=time_axis[p4]
endif
ppp[55]=KEinit; ppp[56]=p4
End

Function CombineForceVideoData()

// needs both contact reference points contact_pF & contact_frame
// operates on current data set using force_mag and compression
// video data is at 50 per second, force data at 500 per second
// so need to average force over 10 points
Wave ppp=ppp,contact_pF=contact_pF,contact_frame=contact_frame
Wave force_mag=force_mag,compression=compression,force_loaded=force_loaded
Wave forceX=forceX,forceY=forceY,forceZ=forceZ,compressX=compressX
Wave compressY=compressY,compressZ=compressZ
Wave/T p_name=p_name
Variable/D p=0,nF=numpnts(force_mag),jNum=ppp[99],sF=contact_pF[jNum]
Variable/D q=0,n=numpnts(compression),dL,force,rest=nF-sF,m2=floor(rest/10)
Variable/D p1,p2,m1=floor(sF/10),sP=contact_frame[jNum]-1,dPEx,dPEy,dPEz,dt=ppp[3]/2,sT
Variable/D c1,c2,F1,F2,tot=0,dPE,test,opt=ppp[85],loaded=force_loaded[jNum]
if(loaded==1)
    Duplicate/O compression force_1 ; force_1=0
    Make/N=(sP+m2)/D/O F_reduced,FXR,FYR,FZR,time_axisFred; F_reduced=NaN
    FXR=NaN; FYR=NaN; FZR=NaN;
    time_axisFred=NaN
    sT=sP*dt // time that force begins
    time_axisFred=x*dt
do
    p1=sF+q*10; p2=p1+10
    WaveStats/R=[p1,p2]/Q force_mag; F_reduced[sP+q]=V_avg
    WaveStats/R=[p1,p2]/Q forceX; FXR[sP+q]=V_avg
    WaveStats/R=[p1,p2]/Q forceY; FYR[sP+q]=V_avg
    WaveStats/R=[p1,p2]/Q forceZ; FZR[sP+q]=V_avg
    q++=1
while(q<m2)
    WaveStats/Q F_reduced; ppp[108]=V_max
    p=0
do
    c1=compression[p]; c2=compression[p+1]
    F1=F_reduced[p]; F2=F_reduced[p+1]
    dL=c2-c1; force=(F1+F2)/2; force_1[p]=force
    c1=compressX[p]; c2=compressX[p+1]
    F1=FXR[p]; F2=FXR[p+1]
    dL=c2-c1; force=(F1+F2)/2
    dPEx=dL*force/100
    c1=compressY[p]; c2=compressY[p+1]
    F1=FZR[p]; F2=FZR[p+1]
    dL=c2-c1; force=(F1+F2)/2
    dPEy=dL*force/100
    c1=compressZ[p]; c2=compressZ[p+1]
    F1=FYR[p]; F2=FYR[p+1]
    dL=c2-c1; force=(F1+F2)/2
    dPEz=dL*force/100
    dPE=dPEx+dPEy+dPEz
```

198
Function ElasticPE()

// calculates pole stored PE from compression and selected pole coefs
Wave ppp=ppp,contact_pF=contact_pF,contact_frame=contact_frame
Wave force_mag=force_mag,compression=compression,PEelastic=PEelastic
Wave/T p_name=p_name
Variable/D p=0,nF=numpnts(force_mag),jNum=ppp[99],sF=contact_pF[jNum]
Variable/D q=0,n=numpnts(compression),dL,force,rest=nF-sF,m2=floor(rest/10)
Variable/D p1,p2,m1=floor(sF/10),sP=contact_frame[jNum]-1,maxloc,xo=ppp[27],lastP=ppp[16]
Variable/D c1,c2,F1,F2,tot=0,dPE,test,opt=ppp[85],poleN=ppp[10],typ,meth=ppp[12],optU=ppp[83]
WaveStats/Q compression; maxloc=V_maxloc // this is the frame where max compression occurs
p=0
PEelastic=0

while(p<lastP+1)
do
c1=compression[p]
test=numtype(c1) // must be 0 for a real number
if(test==0)
   if(p<=maxloc)
      dPE=PoleEnergy(poleN,0,meth,0,c1) // loading
   else
      if(c1<=xo)
         dPE=0
      else
         if(optU==0)
            dPE=PoleEnergy(poleN,0,meth,0,c1)
         else
            dPE=PoleEnergy(poleN,1,meth,xo,c1)
   endif
else
   dPE=0
endif
PEelastic[p]=dPE
p+=1

End

Function PoleBend() // assumes recalled data loaded into X19,Y19,Z19
// and cx0, cy0, cz0
// need pole length and box position
Wave ppp=ppp,length_of_pole=length_of_pole
Wave X19=X19,Y19=Y19,Z19=Z19
Wave Xf19=Xf19,Yf19=Yf19,Zf19=Zf19
Variable/D p=0,n=numpnts(X19),value,opt=ppp[1],conP=ppp[90],maxP
Variable/D boX=ppp[87],boY=ppp[88],boZ=ppp[89],dL,minL=2,lastP=-1,flag=0
Variable/D xx,yy,zz,dx,dy,dz,len,cod=ppp[99],pole_len=length_of_pole[cod]
Make/D/O/N=(n) PoleLength,compression,Pelastic,compressX,compressY,compressZ
PoleLength=NaN; compression=NaN; Peelastic=NaN
compressX=NaN; compressY=NaN; compressZ=NaN
CheckData()
    if(opt==0) // raw data
        Wave wx=X19,wy=Y19,wz=Z19
    else  // filtered data
        Wave wx=Xf19,wy=Yf19,wz=Zf19
    endif
    p=conP-1
    do
        xx=wx[p]; yy=wy[p]; zz=wz[p]
        dx=(xx-boX); dy=(yy-boY); dz=(zz-boZ); len=sqrt(dx^2+dy^2+dz^2)
        PoleLength[p]=len // in cms
        compressX[p]=dx*(pole_len/len-1)
        compressY[p]=dy*(pole_len/len-1)
        compressZ[p]=dz*(pole_len/len-1)
        dL=100*pole_len-len;
        if(flag==0)
            if(p>conP+10)
                if(dL<minL)
                    lastP=p; flag=1
                endif
            endif
        endif
        if(dL<0)
            compressX[p]=nan; compressY[p]=nan; compressZ[p]=nan;
        endif
        compression[p]=dL // cm
        p+=1
    while(p<n)
    ppp[16]=lastP
    WaveStats/Q compression; maxP=V_maxloc; ppp[17]=maxP
    Duplicate/O compression comp_slope
    Differentiate compression/D=comp_slope
End
Function ProcessData() // calculates segment info from markers
    Wave ppp=ppp,s_polarity=s_polarity,Results3D=Results3D
    Wave SSM=SSM,SSF=SSF
    Variable/D p=0,n=numpnts(s_polarity)
    Variable/D pol
    SelectModel()
    p=1
    do
        pol=s_polarity[p]
        if(pol==0) // single
            ProcessSingle(p)
        else // double
            ProcessDouble(p)
        endif
        p++=1
    while(p<n)
    // this generates segment centres cxN,cyN,czN
    // find body centre of mass
    CentreOfMass()
    TranslationalKineticEnergy()
RotationalKineticEnergy()
GravitationalPotentialEnergy()
FindInitialKE()
DoUpdate
Wave j\_KEinit=j\_KEinit, j\_KEinit[frame]=j\_KEinit[frame], j\_PP[frame]=j\_PP[frame]
Variable/D p4=ppp[56], KEinit=ppp[55], cod=ppp[99], conP=ppp[90]
j\_KEinit[cod]=KEinit; j\_KEinit[frame[cod]]=p4; j\_PP[frame[cod]]=conP
Wave contact\_frame=contact\_frame, vaulter\_h=vaulter\_h
Variable/D Ki, Kr, Pg, Kt, t_diff, dt=ppp[3]/2, t1, t2, t3, t4, loaded=0, conF=contact\_frame[cod]
Variable/D nF=ppp[101], max\_h=-1, g=ppp[4], m=ppp[6], pole\_opt=ppp[19]
Variable/D Pts\_b4=ppp[15], nF, v\_h=vaulter\_h[cod], seg\_model\_Num=ppp[7]
// ppp[7] will be the layer in the final Results3D[[1][seg\_model\_Num]]
Kt=ppp[55]; Results3D[cod][0][seg\_model\_Num]=Kt
t4=ppp[56]; Results3D[cod][1][seg\_model\_Num]=t4
WaveStats/Q/R=(conF-pts\_b4, conF) KEtrans; Kt=V\_max; t1=V\_maxloc
WaveStats/Q KErot\_whole; Kt=V\_max; t2=V\_maxloc
Wave KEtrans=KEtrans, KErot\_whole=KErot\_whole
Wave PE\_max\_frame=PE\_max\_frame, PE\_grav\_max=PE\_grav\_max
Wave KE\_trans\_max=KE\_trans\_max, KE\_rot\_max=KE\_rot\_max
Wave trans\_max\_frame=trans\_max\_frame, rot\_max\_frame=rot\_max\_frame
Wave KE\_total=KE\_total, frame\_diff=frame\_diff, PE\_grav=PE\_grav
Wave force\_loaded=force\_loaded, efficiency=efficiency, norm\_h=norm\_h
Wave norm\_KE=norm\_KE, norm\_TE=norm\_TE
Wave contact\_pf=contact\_pf, contact\_lastpf=contact\_lastpf, force\_mag=force\_mag
Variable/D con\_fram1, con\_fram2, xx, yy, dtF=1/500
loaded=force\_loaded[cod]
KE\_trans\_max[cod]=Kt; KE\_rot\_max[cod]=Kr;
norm\_KE[cod]=Kt/m  // joules/kg
trans\_max\_frame[cod]=t1; rot\_max\_frame[cod]=t2
t\_diff=t2-t1; frame\_diff[cod]=t\_diff*dt  // ... better as time?
Make/N=(nF)/D/O KE\_sum; KE\_sum=KE\_trans+KE\_rot\_whole
WaveStats/Q/R=(conF-pts\_b4, conF) KE\_sum; Kt=V\_max; t3=V\_maxloc
KE\_peak[cod]=Kt; peak\_frame[cod]=t3
WaveStats/Q/R=(conF-pts\_b4, conF) KE\_trans; Kt=V\_max; t5=V\_maxloc
Make/N=1/D/O maxKE, maxKE\_t; maxKE=Kt; maxKE\_t=t5/50
WaveStats/Q PE\_grav; Pg=V\_max; t4=V\_maxloc; max\_h=Pg/(m*g)
PE\_grav\_max[cod]=Pg; PE\_max\_frame[cod]=t4; max\_height[cod]=max\_h+ppp[41]/100
ppp[18]=t4; efficiency[cod]=100*Pg/Kt
norm\_h[cod]=100*max\_h/v\_h  // ratio of height jumped to vaulter height both in cms
Duplicate/O KE\_trans TE
if(loaded==1)
  Update\_Force\_Graph()
  Smooth\_Force\_Data()
  Combine\_Force\_Video\_Data()
else
  PE\_elastic=0
endif
Pole\_Bend()
if(pole\_opt==0)
  if(loaded==1)
    Update\_Force\_Graph()
    Smooth\_Force\_Data()
    Combine\_Force\_Video\_Data()
    Make/N=1/D/O force1\_X, force1\_Y, force2\_X, force2\_Y
    con\_fram1=contact\_pf[cod]; con\_fram2=contact\_lastpf[cod]
    xx=con\_fram1*dtF; force1\_X=xx
    yy=force\_mag[con\_fram1]; force1\_Y=yy
    xx=con\_fram2*dtF; force2\_X=xx
    yy=force\_mag[con\_fram2]; force2\_Y=yy
    Force\_Components()
    Find\_Max\_Forces()
else
    PElastic = 0
endif
WaveStats/Q PElastic; ppp[13] = V_max
else
    ElasticPE()
    WaveStats/Q PElastic; ppp[14] = V_max
endif
Wave j_MPB_frame = j_MPB_frame, j_PS_frame = j_PS_frame
Wave j_PR_frame = j_PR_frame, j_hmax_frame = j_hmax_frame
Variable/D lastP = ppp[16], maxP = ppp[17], fram, value
j_MPB_frame[cod] = maxP; j_PS_frame[cod] = lastP; j_hmax_frame[cod] = t4
Wave PElastic = PElastic
TE = PEgrav + KEtrans + KErot_whole + PElastic
Duplicate/O KEtrans Etot
Etot = PEgrav + KEtrans
WaveStats/Q/R = (conF - pts_b4, conF) TE; Kt = V_max; t1 = V_maxloc  */dt
TE_max[cod] = Kt; TE_maxloc[cod] = t1
norm_TE[cod] = Kt/m  // joules/kg
fram = j_PP_frame[cod]; value = TE[fram]; results3D[cod][3][seg_model_Num] = value
fram = j_MPB_frame[cod]; value = TE[fram]; results3D[cod][4][seg_model_Num] = value
fram = j_PS_frame[cod]; value = TE[fram]; results3D[cod][5][seg_model_Num] = value
fram = j_KEinit_frame[cod]; value = TE[fram]; results3D[cod][8][seg_model_Num] = value
fram = j_PP_frame[cod]; value = KEtrans[fram]; results3D[cod][13][seg_model_Num] = value
fram = j_MPB_frame[cod]; value = KEtrans[fram]; results3D[cod][12][seg_model_Num] = value
fram = j_PS_frame[cod]; value = KEtrans[fram]; results3D[cod][10][seg_model_Num] = value
fram = j_hmax_frame[cod]; value = KEtrans[fram]; results3D[cod][11][seg_model_Num] = value
fram = j_KEinit_frame[cod]; value = KErot_whole[fram];
fram = j_PP_frame[cod]; value = KErot_whole[fram];
fram = j_MPB_frame[cod]; value = KErot_whole[fram];
fram = j_PS_frame[cod]; value = KErot_whole[fram];
fram = j_hmax_frame[cod]; value = KErot_whole[fram];
results3D[cod][12][seg_model_Num] = value
fram = j_PP_frame[cod]; value = KErot_whole[fram]; results3D[cod][13][seg_model_Num] = value
fram = j_MPB_frame[cod]; value = KErot_whole[fram];
fram = j_PS_frame[cod]; value = KErot_whole[fram];
results3D[cod][14][seg_model_Num] = value
fram = j_PS_frame[cod]; value = KErot_whole[fram]; results3D[cod][15][seg_model_Num] = value
fram = j_hmax_frame[cod]; value = KErot_whole[fram];
results3D[cod][16][seg_model_Num] = value
fram = j_KEinit_frame[cod]; value = PEgrav[fram]; results3D[cod][17][seg_model_Num] = value
fram = j_PP_frame[cod]; value = PEgrav[fram]; results3D[cod][18][seg_model_Num] = value
fram = j_MPB_frame[cod]; value = PEgrav[fram]; results3D[cod][19][seg_model_Num] = value
fram = j_PS_frame[cod]; value = PEgrav[fram]; results3D[cod][20][seg_model_Num] = value
fram = j_hmax_frame[cod]; value = PEgrav[fram]; results3D[cod][21][seg_model_Num] = value
fram = j_KEinit_frame[cod]; value = Etot[fram]; results3D[cod][22][seg_model_Num] = value
fram = j_PP_frame[cod]; value = Etot[fram]; results3D[cod][23][seg_model_Num] = value
fram = j_MPB_frame[cod]; value = Etot[fram]; results3D[cod][24][seg_model_Num] = value
fram = j_PS_frame[cod]; value = Etot[fram]; results3D[cod][25][seg_model_Num] = value
fram = j_hmax_frame[cod]; value = Etot[fram]; results3D[cod][26][seg_model_Num] = value
DoUpdate
Wave vaulter_num = vaulter_num, vaulter_sex = vaulter_sex, vaulter_level = vaulter_level
Wave j_success = j_success
value = vaulter_num[cod]; results3D[cod][90][seg_model_Num] = value
value = vaulter_sex[cod]; results3D[cod][91][seg_model_Num] = value
value = j_success[cod]; results3D[cod][92][seg_model_Num] = value
value = vaulter_level[cod]; results3D[cod][93][seg_model_Num] = value
End

Function GravitationalPotentialEnergy() // to be done once CentreOfMass() has run
Wave ppp = ppp, cx0 = cx0, cy0 = cy0, cz0 = cz0, v_com = v_com
Variable/D nPts = ppp[101], p = 0, q = 0, dt = ppp[3]
Variable/D x1, x2, y1, y2, z1, z2, msg, opt = ppp[2]
Variable/D yc, PE = 0, g = ppp[4], ymin
Variable/D m = ppp[6]
Make/N=(nPts)/D/O PEgrav; PEgrav=NaN
WaveStats/Q cy0; ycmim=V_min; ppp[41]=ycmin; ppp[42]=V_minloc
p=1
do  
  yc=cy0[p]
  //PE=m*g*(yc-ycmin); PEgrav[p]=PE
  PE=m*g*yc; PEgrav[p]=PE
  p+=1
while(p<nPts-1)  // convert to joules (i.e. cm to m)
End
Function TranslationalKineticEnergy()  // to be done once CentreOfMass() has run
  Wave ppp=ppp,cx0=cx0,cy0=cy0,cz0=cz0,v_com=v_com
  Variable/D nPts=ppp[101],p=0,q=0,dt=ppp[3]
  Variable/D x1,x2,y1,y2,z1,z2,mseg,opt=ppp[2]
  Variable/D xc1,yc1,zc1,xc2,yc2,zc2,dx,dy,dz,v,KE=0
  Variable/D rx1,rx2,ry1,ry2,rr1,rr2,value,tot,m=ppp[6]
  Make/N=(nPts)/D/O KEtrans; KEtrans=NaN
  p=1
  do
    v=v_com[p]
    KE=0.5*m*v^2; KEtrans[p]=KE
    p+=1
  while(p<nPts-1)
  KEtrans*=1e-4  // convert to joules
End
Function RotationalKineticEnergy()  // to be done once CentreOfMass() has run
  Wave ppp=ppp,cx0=cx0,cy0=cy0,cz0=cz0,v_com=v_com
  Wave SSM=SSM,SSF=SSF
  Variable/D nPts=ppp[101],nSeg=numpnts(s_code),p=0,q=0
  Variable/D x1,x2,y1,y2,z1,z2,mseg,opt=ppp[2],vx,vy,vz,vsq,KE=0
  Variable/D rr1,rr2,ry1,ry2,rr1,rr2,value,tot,m=ppp[6],cvx,cvy,cvz,vaulter=ppp[98]
  Make/N=(nPts,nSeg)/D/O KErot; KErot=NaN
  Make/N=(nPts)/D/O KErot_whole; KErot_whole=NaN
  q=1
  do
    String seg=num2str(q),xname="cx"+seg,yname="cy"+seg,zname="cz"+seg
    Wave wx=$xname,wy=$yname,wz=$zname
    mseg=m*SSM[q]/100
    p=1
    do
      x1=wx[p-1]; y1=wy[p-1]; z1=wz[p-1]
      x2=wx[p+1]; y2=wy[p+1]; z2=wz[p+1]
      xc1=cx0[p-1]; yc1=cy0[p-1]; zc1=cz0[p-1]
      xc2=cx0[p+1]; yc2=cy0[p+1]; zc2=cz0[p+1]
      rx1=x1-xc1; rx2=x2-xc2; ry1=y1-yc1; ry2=y2-yc2; rz1=z1-zc1; rz2=z2-zc2
      dx=rx2-rx1; dy=ry2-ry1; dz=rz2-rz1
      vsq=vx^2+vy^2+vz^2
      KE=0.5*mseg*vsq; KErot[p][q]=KE
      p+=1
    while(p<nPts-1)
    q+=1
  while(q<nSeg)
  // total rotational KE
  p=1
  do
    tot=0; q=1
    do
      value=KErot[p][q]; tot+=value
      q+=1
    while(q<nSeg)
  End
while(q<nSeg)
  KErot[p][0]=tot; KErot_whole[p]=tot
  p++
End

while(p<nPts)
  KErot*=1e-4  // convert to joules
  KErot_whole*=1e-4 // convert to joules
End

Function CentreOfMass()
  Wave ppp=ppp,c_of_mass=c_of_mass
  Variable/D p=0,n=ppp[101],xx,yy,zz
  Make/N=(n)/D/O cx0,cy0,cz0
  do
    COM(p)
      xx=c_of_mass[0]; yy=c_of_mass[1]; zz=c_of_mass[2]
      cx0[p]=xx; cy0[p]=yy; cz0[p]=zz
      p++
  while(p<n)
  // CALCULATE VELOCITY
  Variable dt=ppp[3],dx,dy,dz,vx,vy,vz,vv,x1,x2,y1,y2,z1,z2
  Make/N=(n,4)/D/O vdum; vdum=NaN
  p=1
  do
    x1=cx0[p-1]; x2=cx0[p+1]; y1=cy0[p-1]; y2=cy0[p+1]; z1=cz0[p-1]; z2=cz0[p+1]
    dx=x2-x1; dy=y2-y1; dz=z2-z1
    vx=dx/dt; vy=dy/dt; vz=dz/dt;
    vv=sqrt(vx^2+vy^2+vz^2)
    p++
  while(p<n-1)
  Duplicate/O vdum v_com
End

Function COM(frame)  // called from CentreOfMass() for segment model ppp[7]
  Variable frame
  Wave ppp=ppp
  Wave SSM=SSM,SSF=SSF
  Variable/D p=0,n=numpnts(s_code),opt2=ppp[2]
  Variable/D m=ppp[6],dm,f,intX=0,intY=0,intZ=0
  Variable/D xx,yy,zz,seg_mod_num=ppp[7],vaulter=ppp[98]
  String cxname,cyname,czname
  Make/N=3/D/O c_of_mass; c_of_mass=NaN
  p=1  // p=0 is reserved for c.o.m.
  do  // loop over segments
    cxname="cx"+num2str(p)
    cyname="cy"+num2str(p)
    czname="cz"+num2str(p)
    Wave wx=Scxname,wy=Scyname,wz=Sczname
    xx=wx[frame]; yy=wy[frame]; zz=wz[frame]
    dm=SSM[p]*m/100
    intX+=dm*xx; intY+=dm*yy; intZ+=dm*zz
    p++
  while(p<n)
  intX/=m; intY/=m; intZ/=m
End

Function ProcessSingle(k1)  // for head, hands & trunk (polarity = 0)
  Variable k1
  String sname=num2str(k1)
  String wxname="cx"+sname,wyname="cy"+sname,wzname="cz"+sname
  String vname="cv"+sname
  Variable/D frames=ppp[101],k,opt1=ppp[1]
  Wave s_start=s_start
  k=s_start[k1]
String x1name,y1name,z1name
if(opt1==0)
    // using raw data
    x1name="X"+num2str(k)
y1name="Y"+num2str(k)
z1name="Z"+num2str(k)
else
    // using filtered data
    x1name="Xf"+num2str(k)
y1name="Yf"+num2str(k)
z1name="Zf"+num2str(k)
endif
Wave wx1=$x1name,wy1=$y1name,wz1=$z1name
Duplicate/O wx1 Swxname
Duplicate/O wy1 Swyname
Duplicate/O wz1 Swzname

// CALCULATE VELOCITY
Variable dt=ppp[3],dx,dy,dz,vx,vy,vz,vv,p=0,n=numpnts(wx1),x1,x2,y1,y2,z1,z2
// make time axis for graphs
Make/N=(n)/D/O time_axis; time_axis=x*dt/2
Make/N=(n,4)/D/O vdum; vdum=NaN
p=1
do
    x1=wx1[p-1]; x2=wx1[p+1]; y1=wy1[p-1]; y2=wy1[p+1]; z1=wz1[p-1]; z2=wz1[p+1]
    dx=x2-x1; dy=y2-y1; dz=z2-z1
    vx=dx/dt; vy=dy/dt; vz=dz/dt;
    vv=sqrt(vx^2+vy^2+vz^2)
    p+=1
while(p<n-1)
Duplicate/O vdum $wvname
End

Function ProcessDouble(k) // for two markers k1 proximal, k2 distal (polarity = 1)
Variable k
Wave ppp=ppp,s_start=s_start,s_end=s_end
Wave SSM=SSM,SSF=SSF
Variable k1=s_start[k],k2=s_end[k],f
String sname=num2str(k)
Variable opt1=ppp[1],opt2=ppp[2],modNum=ppp[7],vaulter=ppp[98],gender=ppp[2]
String x1name,x2name,y1name,y2name,z1name,z2name
if(opt1==0)
    // using raw data
    x1name="X"+num2str(k1); x2name="X"+num2str(k2)
y1name="Y"+num2str(k1); y2name="Y"+num2str(k2)
z1name="Z"+num2str(k1); z2name="Z"+num2str(k2)
else
    // using filtered data
    x1name="Xf"+num2str(k1); x2name="Xf"+num2str(k2)
y1name="Yf"+num2str(k1); y2name="Yf"+num2str(k2)
z1name="Zf"+num2str(k1); z2name="Zf"+num2str(k2)
endif
Wave wx1=$x1name,wy1=$y1name,wz1=$z1name // proximal point
Wave wx2=$x2name,wy2=$y2name,wz2=$z2name // distal point
Variable n=numpnts(wx1),p=0,x1,x2,y1,y2,z1,z2,xc,yc,zc,len
Make/N=(n)/D/O xdum,ydum,zdum,Ldum,Angdum
xdum=NaN; ydum=NaN; zdum=NaN; Ldum=NaN; Angdum=NaN
f=SSF[k]/100
String wxname="cx"+sname,wyname="cy"+sname,wzname="cz"+sname
String wvname="cv"+sname
do
    x1=wx1[p]; x2=wx2[p]; y1=wy1[p]; y2=wy2[p]; z1=wz1[p]; z2=wz2[p]
    len=sqrt((x2-x1)^2+(y2-y1)^2+(z2-z1)^2); Ldum[p]=len
    xc=x1+dx/2; yc=y1+dy/2; zc=z1+dz/2
    Ldum[p]=sqrt(xc^2+yc^2+zc^2);
    Angdum[p]=atan2(yc,zc); f=SSF[k]/100
    // process double
    // ...
xc=x1+f*(x2-x1); yc=y1+f*(y2-y1); zc=z1+f*(z2-z1)
dxum[p]=xc; ydum[p]=yc; zdum[p]=zc
p++
while(p<n)
Duplicate/O x dum $wxname
Duplicate/O y dum $wyname
Duplicate/O z dum $wzname
// CALCULATE VELOCITY
Variable dt=ppp[3], dx, dy, dz, vx, vy, vz, vv
Make/N=(n,4)/D/O vdum; vdum=NaN
p=1
do
x1=xdum[p-1]; x2=xdum[p+1]; y1=ydum[p-1]; y2=ydum[p+1]
z1=zdum[p-1]; z2=zdum[p+1]
dx=x2-x1; dy=y2-y1; dz=z2-z1
vx=dx/dt; vy=dy/dt; vz=dz/dt; vv=sqrt(vx^2+vy^2+vz^2)
v dum[p][0]=vx; v dum[p][1]=vy; v dum[p][2]=vz; v dum[p][3]=vv
p++
while(p<n-1)
Duplicate/O v dum $wvname
End