

ResearchOnline@JCU

This file is part of the following reference:

Brice, Sara Michelle (2014) *Biomechanical analysis of hammer throwing: assessment of speed development*. PhD thesis, James Cook University.

Access to this file is available from:

<http://researchonline.jcu.edu.au/36292/>

The author has certified to JCU that they have made a reasonable effort to gain permission and acknowledge the owner of any third party copyright material included in this document. If you believe that this is not the case, please contact

*ResearchOnline@jcu.edu.au and quote
<http://researchonline.jcu.edu.au/36292/>*

Biomechanical analysis of hammer throwing:
Assessment of speed development.

Thesis submitted by
Sara Michelle Brice BSc (Hons) JCU
in January 2014

for the degree of Doctor of Philosophy
in the School of Engineering and Physical Sciences
James Cook University

Statement on the contribution of others

I declare that all persons whom have contributed to this thesis have been included as co-authors for published papers or have been identified in the acknowledgments section.

The author of this thesis received stipend support from both James Cook University and the Movement Sciences (Biomechanics) Department of the Australian Institute of Sport. In addition, the Australian Institute of Sport provided the equipment and facilities that were utilised for the data collection of the studies detailed in this thesis.

Supervisors for the work outlined in this thesis are as follows:

- Associate Professor Kevin Ness (Principal Supervisor)¹
- Mr Doug Rosemond (Co-Supervisor)²
- Associate Professor Ronald White (Associate Supervisor)¹

¹Affiliated with the School of Engineering and Physical Sciences of James Cook University

²Affiliated with the Movement Sciences (Biomechanics) Department of the Australian Institute of Sport

The following table is an outline of the contribution of others to the work detailed in this thesis.

Nature of assistance	Contribution	Co-contributors
Intellectual Support	Project design	Mr Doug Rosemond Associate Professor Kevin Ness
	Biomechanical data analysis and interpretation	Mr Doug Rosemond Associate Professor Kevin Ness
	Editing of thesis and/or publications	Associate Professor Kevin Ness Mr Doug Rosemond Dr Yvette Everingham
	Statistical assistance	Dr Yvette Everingham
Data Collection	Equipment design and development	Mr Mark Davis
	Data collection assistance	Mr Doug Rosemond Associate Professor Kevin Ness Staff of the Movement Sciences (Biomechanics) Department of the Australian Institute of Sport

The following outlines the contribution of authors to the co-authored papers that form the basis of some chapters in this thesis.

Chapter	Details of publication on which chapter is based	Intellectual input
4	Brice, S. M., Ness, K. F., & Rosemond, D. (2011). An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers. <i>Sports Biomechanics</i> , 10, 174-184. doi:10.1080/14763141.2011.592210	Sara Brice – Responsible for all data analysis and primary author
		Kevin Ness – Assisted with editing.
		Doug Rosemond – Assisted with editing.
5	Brice, S. M., Ness, K. F., Everingham, Y. L., & Rosemond, D. An analysis of the thorax-pelvis separation angle and its effect on hammer kinetics and kinematics in the hammer throw. Under review.	Sara Brice – Responsible for all data analyses and primary author
		Kevin Ness – Assisted with editing
		Yvette Everingham – Assisted with statistical analyses and with editing Doug Rosemond – Assisted with editing
Chapter	Details of publication on which chapter is based	Intellectual input
6	Brice, S. M., Ness, K. F., & Rosemond, D. Validation of a method to determine hammer speed from cable force in the training environment. <i>Journal of Sport and Health Sciences</i> , In press.	Sara Brice – Responsible for all data analysis and primary author.
		Kevin Ness – Assisted with editing.
		Doug Rosemond – Assisted with editing.

Declaration of Ethics

This research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council (NHMRC) National Statement on Ethical Conduct in Human Research, 2007. The proposed research study received human research ethics approval from the JCU Human Research Ethics Committee Approval Number #H2734 and the Australian Institute of Sport Ethics Committee.

Acknowledgments

First and foremost, I must thank my husband Peter. I know at times my progress has been frustratingly slow, but thank you for standing by me and supporting me while I did this.

My Supervisory team – Kevin Ness and Doug Rosemond. Thank you for all the time you have spent working with me over the years. I really appreciate everything you have both done for me, and I hope we can continue to collaborate in the future.

Mum, Dad and Paula – thank you for supporting me and encouraging me through this. I'm so happy that I can finally say yes to that question Dad!

Elissa, Alison and Ange – thank you for putting up with my occasional rants and being there for me when I needed it. I will never forget the time we spent together in the PhD office.

Staff of the Australian Institute of Sport Movement Science Department – Firstly, thank you for your assistance with data collection, and thank you to all those that taught me so much during my time working with you.

Abstract

The aim of the hammer throw is to project the hammer as far as possible and, major contributing factor to throw success is the speed of the hammer at the instant of release. The thrower accelerates the hammer to the instant of release by performing turns across the hammer throw circle, during which time the hammer's linear speed fluctuates. The first two studies of this thesis were concerned with ascertaining how an athlete could improve speed development in the hammer throw while the third study was focused on development and validation of a system that would facilitate direct measurement of speed development in the training environment.

Study one focused on assessing the relationship between the hammer's linear speed and the thrower applied cable force. This was done to identify how cable force magnitude and direction affects the speed development, specifically losses. Speed losses occur when the tangential component of the cable force (tangential force) is negative. The loss of speed caused by the negative tangential force can be reduced in two ways: by decreasing the magnitude of the negative tangential force itself or by decreasing the amount time that it acts for. Results of this study indicate that it is more effective for a thrower to decrease the magnitude of the negative tangential force. Throwers can do this by reducing either the cable force magnitude or by the angle between the cable force and linear hammer velocity. The findings presented here indicate that the most effective way to minimise the impact of negative tangential force is to reduce the angle.

Study two was concerned with identifying how a thrower could alter their technique so as to lead to a reduction in the size of losses in speed. In this study, the relationship between speed losses and movement of the throwers thorax relative to the pelvis (thorax-pelvis separation angle) was investigated. The results of this study indicate that throwers should aim to reduce the size of the thorax-pelvis separation angle during double support, specifically during turn two and the second last turn. This was found to result in a smaller loss in speed during the subsequent single support phase.

The aim of study three was to develop and validate a method that would facilitate accurate feedback of linear hammer speed within the training environment as this would allow athletes and coaches to implement the technique changes outlined in study two and assess how these changes affect hammer speed. The most accurate way to determine hammer speed is via hammer three-dimensional position data; however, current methods of collecting these data do not allow provision of immediate feedback. In this study, a method that would allow speed to be determined from cable force information was sought as methods that allow immediate feedback on cable force data have already been validated.

Two linear regression models were developed that allowed linear hammer speed to be predicted from cable force data. Both of the developed models were found to be reliable at predicting speed from force data. Therefore, either model could be utilised, in conjunction with a device that allows direct measurement of cable force, to provide immediate feedback on linear hammer speed in the training environment.

Table of contents

Statement on the contribution of others	ii
Declaration of Ethics	iv
Acknowledgments	v
Abstract.....	vi
Table of contents.....	ix
List of Tables.....	xii
List of Figures.....	xiii
Nomenclature.....	xvi
Chapter 1 – Introduction.....	1
1.1 Introduction.....	1
1.2 Historic origins of the hammer throw	1
1.3 Modern hammer throw technique and equipment	3
1.4 Purpose of this study	7
1.5 Significance of this study	8
1.6 Thesis Outline.....	9
Chapter 2 – A review of the biomechanical aspects of the hammer throw.	12
2.1 Introduction.....	12
2.2 Projectile motion	14
2.3 Kinematics of the hammer throw	20
2.3.1 Linear speed development.....	20
2.3.2 Angular kinematics.....	22
2.3.3 Mechanics of the hammer, thrower and hammer-thrower systems..	27
2.4 Kinetics of the hammer throw	29
2.4.2 Forces acting on the hammer	29
2.4.2 Forces acting on the thrower.....	33
2.4.3 Forces acting on the hammer-thrower system	35
Chapter 3 – Data acquisition	37
3.1 Introduction.....	37
3.2 Experimental overview.....	37
3.4 Data acquisition procedures	39
3.4.1 Three-dimensional positional data acquisition	39
3.4.2 Cable force direct measurement procedures	44
3.5 Data processing procedures.....	46
3.5.1 Three-dimensional data processing procedures	46

3.5.2 Measured force data processing procedures.....	47
3.5.3 Hammer head position calculation procedures	48
Chapter 4 – An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers.	50
4.1 Chapter Statement	50
4.2 Introduction.....	51
4.3 Methods.....	53
4.4 Results.....	57
4.5 Discussion and Implications	63
4.6 Conclusion.....	70
4.7 Chapter Summary	70
Chapter 5 – An analysis of the thorax-pelvis separation angle and its effect on hammer kinetics and kinematics in the hammer throw.....	72
5.1 Chapter Statement	72
5.2 Introduction.....	73
5.3 Methods.....	76
5.4 Results.....	80
5.5 Discussion and Implications	87
5.6 Conclusion.....	91
5.7 Chapter Summary	91
Chapter 6 – Validation of a method to determine hammer speed from cable force in the training environment.	93
6.1 Chapter statement	93
6.2 Introduction.....	94
6.3 Methods.....	97
6.4 Results.....	101
6.5 Discussion and Implications	102
6.6 Conclusion.....	105
6.7 Chapter Summary	105
Chapter 7 – Epilogue	107
7.1 Introduction.....	107
7.2 Key findings and Implications.	107
7.2.1 Relationship between the linear hammer speed and the thrower applied forces.....	107
7.2.2 Relationship between thorax-pelvis separation angle and hammer kinetics and kinematics in the hammer throw.....	108
7.2.3 Predicting linear hammer speed in the training environment	109
7.3 Limitations and recommendations for future research.....	111

7.4 Conclusion.....	112
Chapter 8 – Bibliography.....	113
Appendices	126
Appendix A: Participant Information Sheet and Informed Consent Form. ...	126
Appendix B: Publication of Chapter 4	132
Appendix C: Publication of Chapter 5.....	147
Appendix D: Publication of Chapter 6.....	160

List of Tables

Table	Title of table	Page no.
Table 2.1a	Variation of release angle (in degrees) with release heights and release speeds relevant to the hammer throw. Angles are determined using equation (2.1).	18
Table 2.1b	Variation of release angle (in degrees) with release heights and ranges relevant to the hammer throw. Angles are determined using equation (2.2).	18
Table 2.2	Variation in ranges (in metres) calculated via equation (1.1) using release angles and speeds relevant to the hammer throw. Release height is set at 1.70 m.	20
Table 3.1	Gender, handedness, mass, height and number of turns used by each athlete who participated in the studies of this thesis.	39
Table 3.2	Plug-In Gait model marker names and marker location definitions. *number of the markers displayed in Figure 3.1.	41
Table 3.3	Description of specific anatomical measurements required for the Plug-In Gait model.	44
Table 4.1	Gender averages of distance thrown, distance of best throw produced, release speed, peak cable force and peak force normalised for hammer weight in this study. Standard deviations indicated in brackets.	57
Table 5.1	Turn number used in each of the correlation analyses of this study.	79
Table 5.2	Persons correlation coefficients for relationship between thorax-pelvis separation angle at its smallest within each turn and selected hammer kinetic and kinematic variables.	85
Table 6.1	Regression equations used to predict speed squared from normalised measured force data, the coefficient of multiple correlation (CMC) and the root mean square (RMS) of the difference between the calculated speed and the predicted speed. The numbers in the table show the means and associated standard deviations of the individual throws. Standard deviations indicated in brackets.	102

List of Figures

Figure	Title of figure	Page no.
Figure 1.1	Dimensions of the hammer throw circle and throwing sector.	3
Figure 1.2	Schematic diagram of the (a) hammer and (b) hammer's handle	4
Figure 1.3	Overhead view of the reference points used when describing the hammer throw.	5
Figure 1.4	Key instances during the hammer throw: (a) start of entry, (b) single support phase (c) double support phase and (d) point of release for a right handed thrower.	6
Figure 2.1	Graph of the hammer speed from entry through until release for a typical throw of a four turn thrower (Brice, 2006).	21
Figure 2.2	Graph of the linear speed, angular hammer speed and the radius of rotation from entry through to release for a typical throw of a four turn thrower (Brice 2006).	24
Figure 2.3	Body positions during the double support phase for the two different throwing techniques described by Dapena and McDonald (1989) where throwers (a) counter with their shoulders and (b) counter with their hips.	26
Figure 2.4	Graph of the cable force from entry through until release for a typical throw of a four turn thrower (Brice, 2006).	30
Figure 2.5	Radial and tangential components of the cable force when the cable force vector is pulling in front of the direction of the radius of rotation (a) and when pulling behind (b). The normal component acts perpendicular to the plane of motion in both (a) and (b) and always points upwards as the normal component of the gravity vector always acts downwards.	32
Figure 3.1	Plug-In Gait marker placement.	40
Figure 3.2	Field testing area. Throw direction is from left to right.	42
Figure 3.3	Global reference frame used in each of the studies of this thesis. The z -axis is perpendicular to the ground and the origin was located roughly at the centre of the throwing circle.	42
Figure 3.4	Strain gauge calibration rig. Note: the hammer ball and handle were detached from the cable throughout the calibration procedure.	45

Figure 3.5	Retro-reflective markers positioned on the hammer's cable at points $p_1 = (x_1, y_1, z_1)$ and $p_2 = (x_2, y_2, z_2)$. d_1 is the radius of the hammer's head (varied depending on which hammer head was used), d_2 is the distance between the point closest to the hammer head and the end of the hammer cable ($d_2 = 0.25$ m) and d_3 is the distance between the two points ($d_3 = 0.45$ m).	48
Figure 4.1	Radial and tangential components of the cable force when the cable force vector is pulling in front of the direction of the radius of rotation (a) and when it is pulling behind (b). The normal component acts perpendicular to the plane of motion in both (a) and (b).	51
Figure 4.2	Hammer speed and vertical height of the hammer's head from entry through to release for the best throw of: (a) male three turn thrower (63.22 m), (b) male four turn thrower (61.45 m), (c) female four turn thrower (59.86 m) and (d) female five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete is in double support.	58
Figure 4.3	Cable force magnitude and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 4.2.	59
Figure 4.4	Tangential force and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 4.2.	59
Figure 4.5	Scattergrams of correlate data: (a) decrease in normalised cable force vs. loss in hammer speed, (b) increase in normalised cable force vs. increase in speed (c) decrease in normalised cable force vs decrease in normalised tangential force, (d) normalised tangential force at its most negative vs. loss in hammer speed, (e) time applying negative tangential force vs. loss in hammer speed, (f) normalised tangential force at its most positive vs. increase in speed (g) loss in hammer speed vs. the magnitude of angle β at its maximum in each turn (h) loss in hammer speed vs. normalised cable force, when β is at its maximum in each turn (i) increase in hammer speed in subsequent turn vs. the magnitude of angle β at its maximum in the previous turn.	62
Figure 5.1	Overhead view of the thorax-pelvis separation angle. Angle is defined as being (a) negative (pelvis leading thorax) and (b) positive (thorax leading pelvis) for a right-handed thrower.	78

Figure 5.2	Thorax-pelvis separation angle for the furthest throw of the male participants: (a) three turn thrower (63.22 m), (b) four turn thrower (61.45 m), (c) four turn thrower (60.71 m), (d) three turn thrower (57.69 m) and (e) four turn thrower (42.61 m). Note: black lines at the bottom of each graph indicate when the athlete was in double support.	81
Figure 5.3	Traces of the thorax-pelvis separation angle for the furthest throw of female participants: (a) four turn thrower (59.86 m), (b) four turn thrower (57.59 m), (c) four turn thrower (55.66 m), (d) four turn thrower (54.54 m) and (e) five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete was in double support.	82
Figure 5.4	Scatterplots of data used to obtain correlations between minimum separation angle and normalised tangential force at its minimum (F_{min} in Table 5.2) in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.	86
Figure 5.5	Scatterplots of data used to obtain correlations between minimum separation angle and the subsequent loss in speed in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.	86
Figure 5.6	Scatterplots of data used to obtain correlations between minimum separation angle and β at its maximum in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.	87
Figure 6.1	Schematic of the data processing undertaken to validate the predicted speed data.	101
Figure 6.2	Traces of calculated speed and predicted speeds from a single trial of a male participant.	103

Nomenclature

Term	Definition
v	Linear hammer velocity.
r	Distance between the centre of mass of the hammer and the axis of rotation (radius of rotation or radius of curvature).
F_C	Force exerted by the thrower on the hammer (cable force)
F_{CR}	Radial component of the cable force.
F_{CT}	Tangential component of the cable force (tangential force).
β	Angle between F_C and v .
F	Centripetal force.
RMS	Root mean square of the differences.
CMC	Coefficient of multiple correlation.
Thorax-pelvis separation angle	Angle between the frontal planes of the thorax and pelvis segments.
Single support	Period of time during a turn where the thrower has one foot in contact with the ground.
Double support	Period of time during a turn where the thrower has both feet in contact with the ground.
Calculated speed	Linear hammer speed determined from three-dimensional coordinate data for the centre of the hammer's head.
Predicted speed	Linear hammer speed derived using a linear regression model (outlined in Chapter 6) and measured F_C data.

Chapter 1 – Introduction

1.1 Introduction

The first part of this chapter outlines the historic origins of the hammer throw (section 1.1) and provides a brief overview of modern hammer throw technique and the associated equipment (section 1.2). The second part of the chapter outlines the purpose (section 1.3) and significance (section 1.4) of this thesis (section 1.3) and finishes with a brief overview of the scope of the remaining chapters (section 1.5).

1.2 Historic origins of the hammer throw

The origins of the hammer throw date back to 2000BC where a hammer type event was featured in the Irish Tailteann games (Johnson, 1969; Tancred & Carter, 1980). While this event is regarded as the origin of the sport, the hammer throw event contested at the Scottish highland games is more closely related to the modern hammer throw. Initially, chariot wheels were thrown until the introduction of throwing blacksmith's hammers and sledge hammers.

During the 1860's, a standardised circular, grass throwing area (which later became concrete in 1953) was introduced (Johnson, 1969; Tancred & Carter, 1980). The sledge hammer was also replaced at this time with a wooden shaft that had a cross-piece or loop for a hand grip at one end, and a round iron ball positioned at the other end (Johnson, 1969; Tancred & Carter, 1980). Further

changes to the hammer were made in 1887 when the hammer became an iron ball connected to a triangular handle by means of a chain or wire with restrictions being given to the length (1.22m) and weight (7.257kg) (Johnson, 1969; Tancred & Carter, 1980).

The technique utilised by throwers has also undergone numerous changes over the years. The first reported technique was a standing release technique where throwers stood side-on to the direction of the throw and would accelerate the hammer by swinging it from side to side in front of them prior to releasing the implement (Tancred & Carter, 1980). This technique was discarded in the 1860's and replaced with a technique where throwers would swing the hammer around their heads prior to release; a technique still used today in the highland games (Babbitt, 2003; Johnson, 1969; Tancred & Carter, 1980).

By 1927, throwers had adopted a heel/toe footwork technique where the thrower would perform turns across the throwing circle. This technique resulted in the turns being performed at a much faster rate (Bartonietz, 2000). Around 1954, Irish-American Hal Connolly introduced the technique that is currently utilised by throwers where the thrower turns on the outside of the foot while progressively sinking deeper into a squatting position to gain a more powerful leg lift (Tancred & Carter, 1980).

1.3 Modern hammer throw technique and equipment

The modern hammer throw is one of the four track and field throwing disciplines. As with the other three throwing disciplines, the aim of the hammer throw is to project the hammer as far as possible without committing a foul. A throw is deemed to be a foul if the hammer lands outside the sector lines (Figure 1.1) or if the athlete steps outside the front half of the throwing circle at any point during or just after a throw has been completed. As was mentioned above, modern hammer throwers accelerate the hammer to the point of release by performing turns across the throwing circle (Tancred & Carter, 1980). Within each individual turn there are periods where the speed will both increase and decrease in magnitude. The kinematics and kinetics associated with how a thrower accelerates the hammer are detailed in Chapter 2 of this thesis.

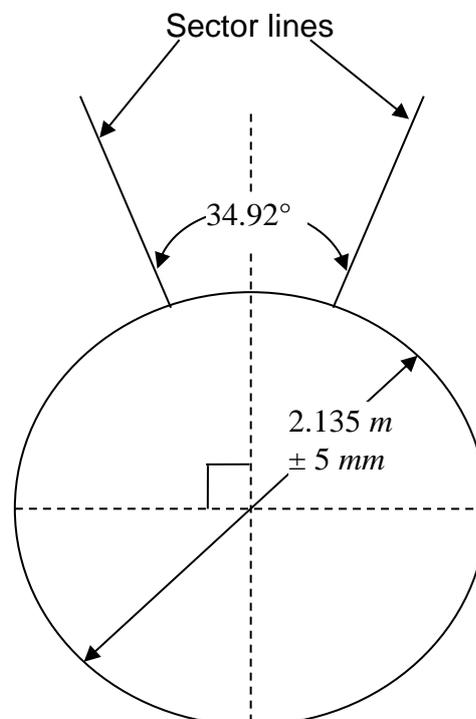


Figure 1.1. Dimensions of the hammer throw circle and throwing sector.

The hammer consists of a metal ball (head) and triangular handle that are connected by a steel cable (Figure 1.2a). The head is made of solid iron or some other type of metal that is no softer than brass. Alternately the head can be a shell of metal filled with lead or some other solid material. The head, cable and handle of a competition standard hammer must weigh a combined total of 7.26 kg for males and 4.00 kg for females. The diameter of the hammer's head must be is between 110 – 130 mm for males and 95 – 100 mm for females. The handles used by both genders are identical and can have a maximum length of 110 mm (Figure 1.2b). The total length of the hammer is measured from the inside of the handle grip to the end of the hammer's head and must be between 1175 – 1215 mm for males and 1160 – 1195 mm for females. Further information about specifications and competition rules are outlined in the International Association of Athletics Federations (IAAF) Rulebook (IAAF, 2010).

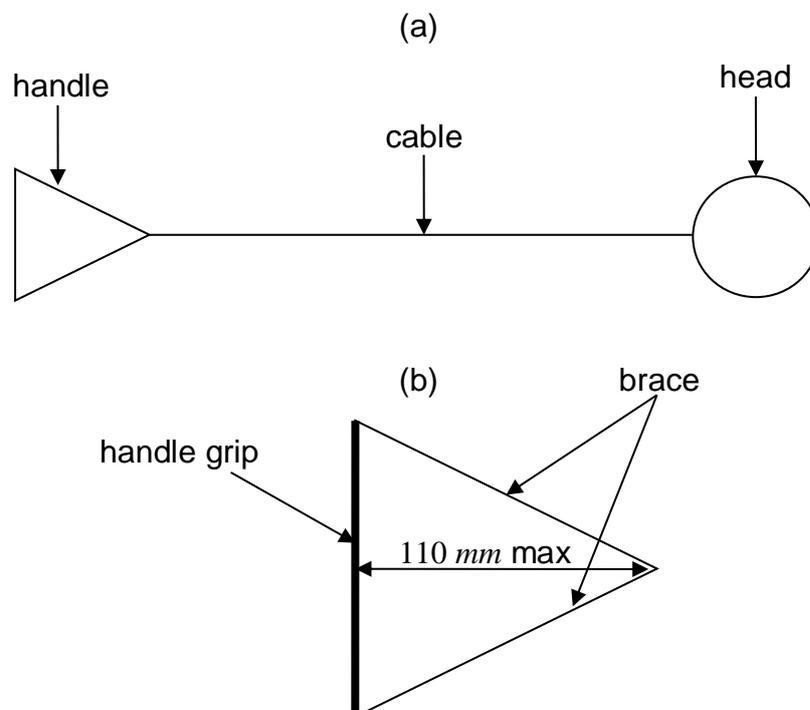


Figure 1.2. Schematic diagram of the (a) hammer and (b) hammer's handle

Athletes commence a throw by performing preliminary swings where they swing the hammer overhead in a circular arc while facing the rear of the circle (0° in Figure 1.3). The aim of the preliminary swings is to give the hammer the proper plane and to establish the “low point” (in front of the right foot for a right handed thrower) (Simonyi, 1980). Throwers should also ensure that the path the hammer undertakes is maximised during the swings and that the speed of the swings is optimal as this is important for establishing the rhythm of the throw (Connolly, 1996; Jaede, 1991; Morley, 2003a). The transition from the preliminary swings into the first turn is called the entry or transfer phase (Figure 1.4a), and this is crucial to throw success (Judge, 2000a). During this time, the thrower lowers his/her centre of gravity and rotates the hammer around from 270° to 90° (for a right handed thrower) while ensuring that both feet are kept on the ground.

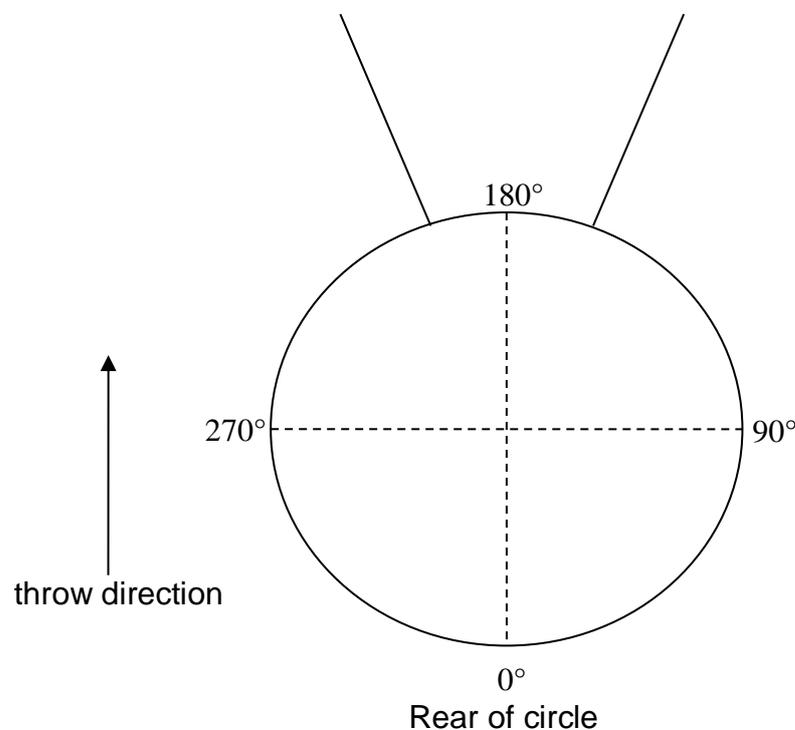


Figure 1.3. Overhead view of the reference points used when describing the hammer throw.

The thrower continues to accelerate the hammer by performing 360° turns across the throwing circle. Typically, elite throwers will perform three or four turns; however, a less common five turn technique can also be utilised. Each individual turn consists of a phase of single support (Figure 1.4b), where one foot is on the ground (left foot for a right handed thrower), and double support, where both feet on the ground (Figure 1.4c). The number of turns a thrower uses varies depending on ability, level of speed and strength (Judge, 2000b).

The final part of the hammer throw is the delivery phase which commences at the end of the final turn and culminates with the release of the hammer. During this time, the thrower accelerates the hammer upwards, as it passes through 0°, and over their shoulder (left for right handed thrower, Figure 1.4d). The thrower does this by extending the knees, hips, back and shoulders (Judge, 2000b, Morley, 2003b) with the hammer being released at approximately shoulder height (Otto, 1991; Bartonietz, Barclay & Gathercole, 1997).

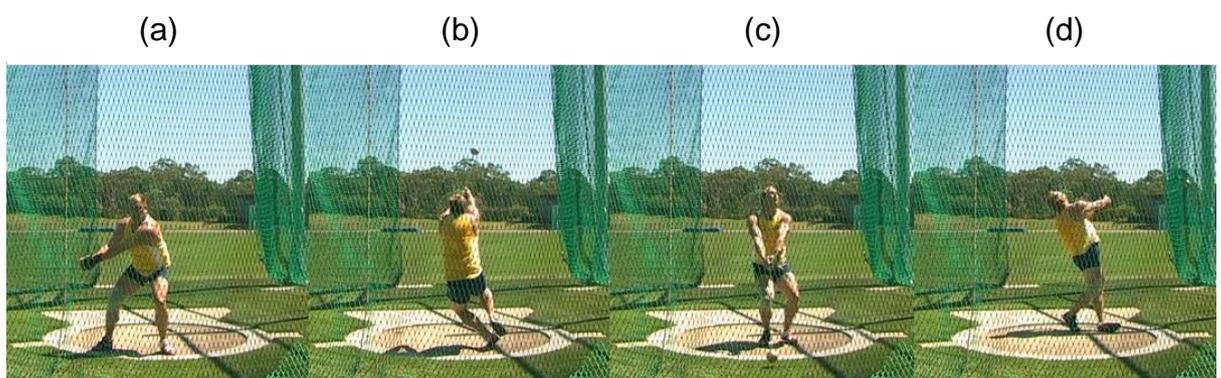


Figure 1.4. Key instances during the hammer throw: (a) start of entry, (b) single support phase (c) double support phase and (d) point of release for a right handed thrower.

1.4 Purpose of this study

Once the hammer has been released, it undergoes projectile motion. If aerodynamic forces are ignored, the distance it will travel (R) can be determined via the following equation (Hubbard, 2000),

$$R = v_0^2 \cos \theta \frac{\left[\sin \theta + \sqrt{\sin^2 \theta + \frac{2gh_0}{v_0^2}} \right]}{g} \quad (1.1)$$

where v_0 is the magnitude of the hammer's linear velocity at release, g is the acceleration due to gravity, θ is the angle the hammer makes with the horizontal at the instant of release and h_0 is the height of the hammer at release. Both the height and angle terms in equation 1.1 can be optimised whereas the thrower can continually improve the release speed.

Once a thrower has developed a technique that consistently results in optimal values for release height and angle, it follows that emphasis should then be placed on technique alterations that can lead to improvement of the release speed. Consequently, three specific aims were proposed for this thesis with the primary objective being to identify elements of a thrower's technique that could be altered to potentially improve speed development and release speed in the hammer throw. The intention of the first two aims was to identify the specific technique alterations. The intention of the third aim was to develop an accurate method that would allow direct assessment of how the technique changes, identified as a result of the first two aims, affected speed development in the training environment.

The specific aims are:

1 – To examine speed development in the hammer throw and investigate the relationship between overall speed development and kinetics and kinematics of the hammer.

2 – To investigate the relationship between thrower movement kinematics and the identified hammer kinetic and kinematic parameters that influence speed development.

3 – To develop and validate a method that directly measures speed development in the hammer throw to allow accurate assessment of how changes to technique effect overall speed development.

1.5 Significance of this study

A search of the literature into the biomechanical aspects of the hammer throw indicates that the 1980's was the most productive period for both coaching style articles and biomechanical research papers (Brice et al. 2008). Technology has evolved significantly since this time, and while the quality of this past work is not in question, these concepts need to be revisited (Riley & Doyle, 2005). In the studies that encompass this thesis, speed development in the hammer throw was revisited.

This thesis investigates the relationship between the biomechanical elements of the hammer and overall speed development. It also identifies aspects of the thrower's kinematics that are related to, and could potentially improve, speed development in the hammer throw. This is beneficial to athletes and coaches as it presents specific, scientific based information on how a thrower could alter technique and enhance performance in the hammer throw.

This thesis also presents the details of a valid and reliable method that allows direct measurement of speed development in the hammer throw. This is useful to athletes and coaches as it can be used to assess how technique changes are effecting speed development. In addition, it is also a method that allows immediate feedback within the training environment; the importance of which has been highlighted numerous times in the literature.

1.6 Thesis Outline

The thesis begins with an introductory chapter (Chapter 1) that gives a brief summary of the historic origins of hammer throwing followed by a general overview of modern hammer throwing. This is followed an outline of the purpose and significance of this body of work. The subsequent chapter (Chapter 2) presents a review of the literature encompassing the biomechanical aspects of the hammer throw and the typical characteristics of elite hammer throwers. The third chapter (Chapter 3) provides a detailed description of the data collection and processing procedures utilised for each of the studies presented in this thesis. The following three chapters present the findings of the three separate

studies that answer the identified research questions of this body of work. The primary focus of each study was to address one of the three aims outlined in section 1.4.

Study one (Chapter 4) was concerned with the first of the three aims. The purpose of this first study was to quantify the strength of the relationship between the force the thrower applies to the hammer (cable force) and hammer speed. In addition to this, how the magnitude and direction of the cable force affects the fluctuations in hammer speed was also investigated in this study. The findings presented within this chapter were used to classify what were considered key elements of the hammer's kinetics and kinematics in terms of speed development in the hammer throw.

The second study (Chapter 5) addresses the second of the three aims which was to investigate the relationship between thrower movement kinematics and key elements of the hammer's kinetics and kinematics that influence speed development. Thorax-pelvis separation was the aspect of the thrower's movement kinematics that was analysed in this study while the key elements of the hammer's kinetics and kinematics were identified in the first study. Thorax-pelvis separation angle was chosen for analysis as it was hypothesised that with training an athlete could easily manipulate this variable. The findings presented in this chapter give athletes and coaches a clear indication as to how a thrower could enhance speed development, by making changes to the thorax-pelvis separation angle at key instances in the throw.

The first two studies focused on ascertaining what technique adaptations could be utilised by the thrower to enhance speed development. The purpose of the final study (Chapter 6) was to develop and validate a method that allows hammer speed to be determined in the training environment for immediate feedback purposes. This system could be used to assist athletes and coaches with assessing how the technique changes, proposed in Chapter 5, are effecting speed development.

In the final chapter (Chapter 7) of this body of work, a synthesis of the results is provided along with an overview of the practical applications of the findings presented in this thesis and recommendations for future hammer throw research.

Chapter 2 – A review of the biomechanical aspects of the hammer throw.

2.1 Introduction

Two important attributes of hammer throwers are strength and power (Riley & Doyle, 2005). Whilst physical condition and athleticism are both imperative, it is also important to acknowledge the significant contribution of an athlete's technical ability to overall performance (Dapena, 1984; Judge, Hunter & Gilreath, 2008; Simonyi, 1980). At the elite level of the sport, it is also widely believed that technique is the largest discriminating factor between athletes (Morriss & Bartlett, 1992). In recent times, it has been suggested that too much emphasis has been placed by coaches on strength and power at the expense of technique (Riley & Doyle, 2005). In addition, it has been argued in the literature that a lack of scientific research into hammer throw technique is hindering the development of the sport (Riley & Doyle, 2005).

Analysis of the progression of the world record in the men's event shows a steady increase from when the discipline was first introduced as an Olympic event in 1900 until midway through the 1980's. During the late 1980's, Bartonietz et al. (1988) indicated it was a certainty that the 90 m mark would be surpassed in the men's event. While the years have progressed, the 1986 world record of 86.74 m set by Yuriy Sedykh currently still stands. In the literature,

there have been a number of reasons proposed for this lack of progression. The first is that this record was set prior to the introduction of stringent drug testing standards, which has led some observers to believe that the record set by Sedykh may be “drug tainted” (Riley & Doyle, 2005). The second reason is that the current training models utilised by many coaches involve the introduction of strength training at a much younger age, which has resulted in there being less emphasis on skill acquisition (Riley & Doyle, 2005).

In order for there to be further progression in the sport, it is thought that coaches need to adopt a more critical, scientific approach to assist with more accurate technical adjustments (Judge, Hunter & Gilreath, 2008). In addition, there needs to be development of clearer guidelines for technique optimisation, without which the hammer throw can only be advanced through trial and error (Riley & Doyle, 2005).

Hammer throwing is a complicated event in which the laws of mechanics play an important role. Therefore, athletes and coaches must have a sound understanding of the laws behind the event to allow technique advancement (Simonyi, 1980). In this chapter, a review of the biomechanical aspects of the hammer throw is given by first considering the projectile motion of the hammer after release followed by investigation into the kinematics and kinetics of the hammer, thrower and hammer-thrower system.

2.2 Projectile motion

As was pointed out in section 1.4, once the hammer is released, it undergoes projectile motion. There are two types of forces that will act on a projectile: gravity and aerodynamic forces (Dapena & Teves, 1982). Gravity acts vertically downwards, and its magnitude remains unchanged throughout the projectile's motion while the aerodynamic forces will vary depending on a number of factors. There are two aerodynamic forces that will act on a hammer once released: drag and lift (Dapena & Teves, 1982). The magnitude and direction of the drag force (air resistance) will vary depending on environmental factors such as the wind direction; however, in the absence of wind this vector acts in the opposite direction to the linear hammer velocity vector (opposite to the throw direction). The lift force acting on the hammer is due to the Magnus effect and is assumed to be insignificant when compared to the other forces that are present (Dapena & Teves, 1982).

The aerodynamicity of an object is a measure of the maximum acceleration possible from aerodynamic forces during flight (Hubbard, 1989). For the hammer, the aerodynamicity has been reported as being 0.74 m/s^2 which indicates that a zero drag assumption is incorrect when estimating range or throw distance in the hammer throw (Hubbard, 1989). Therefore, it follows that ignoring air resistance in range calculations will lead to an overestimate in distance thrown (Dapena et al. 2003).

A number of studies have assessed the effect of aerodynamic forces on range in the hammer throw. De Mestre (1990) and Hubbard (1989) derived two different analytical solutions to determine the effect of air resistance on range. Hubbard (1989) reported that inclusion of air resistance in the calculation resulted in an approximate reduction of 6% in the range of a 7.26 kg hammer while De Mestre's (1990) analytical solution resulted in ranges that were approximately 2% smaller. None of the results of these two models were compared with data from actual throws.

More recently, Dapena et al. (2003) further investigated the effect of air resistance on range. In this study, they utilised data from actual throws which allowed them to compare the ranges derived via models with the actual throw distance. The effect of air resistance resulted in reductions of 4% for a male's 75 m throw and 6% for a female's 73 m throw. In addition, they also applied the analytical solutions reported by Hubbard (1989) and De Mestre (1990) and found they overestimate and underestimate, respectively, the effect that air resistance has on range (Dapena et al. 2003).

On any day of competition, the effect of the aforementioned aerodynamic forces will essentially be the same for all throwers of similar ability. In addition, the magnitude of the aerodynamic forces is something that a thrower is unable to control. Therefore, it is useful to investigate the release parameters that govern throw distance in the absence of the aerodynamic forces as the release parameters are something a thrower can actively manipulate.

If aerodynamic forces are ignored, the aerodynamicity is equal to zero which in turn results in the trajectory of the hammer being parabolic (Hubbard, 1989). In addition, the only force that needs to be considered under these conditions is gravity; hence the hammer is undergoing a constant acceleration. For any projectile, the motion can be resolved into the horizontal and vertical components. Analysis of the equation that describes the horizontal displacement or range (equation (1.1)) indicates that the kinematic parameters at release that effect the range in the hammer throw are the linear velocity of the hammer, the angle the linear velocity vector makes with the horizontal and the height at which the hammer is released at above the ground (Bartonietz, Barclay & Gathercole, 1997; Bartonietz et al. 1988; Dapena, 1989; Dapena et al. 2003; Jabs, 1979; Maroński, 1991; Morriss & Bartlett, 1995a, 1995b; Ohta et al. 2010; Otto, 1991).

Inspection of equation (1.1) shows that increasing release velocity and/or release height causes an increase in throw range (Lichtenberg & Wills, 1978). However, in order for the range to be as large as possible, throwers should ensure that all three release parameters are optimised. If an optimal value for each parameter exists, it can be determined by differentiating equation (1.1) with respect to each parameter and setting the derivative equal to zero. Differentiating this equation with respect to release velocity and release height shows there are no optimal values for these variables. This indicates that linear velocity and height at release should be as large as possible (Hubbard, 2000). This is not the case for the release angle which, for a given velocity and height,

can have an optimal value that will maximise the range (Hubbard, 2000; Lichtenberg & Wills, 1978).

If a projectile is released from ground level (i.e. $h_0 = 0$ m in equation (1.1)) then the range will be maximised if the release angle is equal to 45° (De Mestre, 1990). If, however, the projectile is released from a height that is higher than the landing height, as is the case in the hammer throw, the optimal release angle will always be less than 45° . Differentiating equation (1.1) with respect to the release angle and setting the resultant derivative equal to zero yields the following,

$$\sin \theta = \frac{1}{\sqrt{2}} \left(1 + \frac{gh_0}{v_0^2} \right)^{-\frac{1}{2}} \quad (2.1)$$

Using equation (2.1) and release speeds and heights relevant to the hammer throw shows there is little variation in the optimal release angle (Table 2.1a). The optimal angles fall within a narrow range between 44.15° and 44.56° (Table 2.1a). This is also evident when optimal release angles are determined using the following simplified equation for range (Lichtenberg & Wills, 1978),

$$R = h_0 \tan 2\theta. \quad (2.2)$$

The above equation is derived by solving equation (2.1) for speed and substituting for speed in equation (1.1). Optimal angles determined via equation (2.2), using release heights and ranges relevant to the hammer throw show that the angle again varies in a narrow range between 44.20° and 44.55° (Table 2.1b). These values and those reported in Table 2.1a support what has been previously reported in the literature that the optimal release angle is close to 44° (Bartonietz et al. 1988; Johnson, 1969; Otto, 1991). However, female throwers

tend to have a much flatter release than their male counterparts most probably due to an unfavourable relationship between implement length and height (Bartonietz, 2000; Bartonietz, Barclay & Gathercole, 1997).

Table 2.1a. Variation of release angle (in degrees) with release heights and release speeds relevant to the hammer throw. Angles are determined using equation (2.1).

← Height (m)	Speed (m/s) →					
	25	26	27	28	29	30
1.5	44.36	44.41	44.46	44.49	44.53	44.56
1.6	44.32	44.37	44.42	44.46	44.5	44.53
1.7	44.28	44.33	44.38	44.43	44.47	44.5
1.8	44.24	44.29	44.34	44.39	44.43	44.47
1.9	44.19	44.25	44.31	44.36	44.4	44.44
2	44.15	44.21	44.27	44.32	44.37	44.41

Table 2.1b. Variation of release angle (in degrees) with release heights and ranges relevant to the hammer throw. Angles are determined using equation (2.2).

← Range (m)	Height (m) →					
	1.50	1.60	1.70	1.80	1.90	2.00
70.0	44.41	44.37	44.33	44.29	44.25	44.20
72.0	44.43	44.39	44.35	44.31	44.27	44.23
74.0	44.44	44.4	44.36	44.33	44.29	44.25
76.0	44.46	44.42	44.38	44.34	44.31	44.27
78.0	44.47	44.43	44.4	44.36	44.32	44.29
80.0	44.49	44.45	44.41	44.38	44.34	44.31
82.0	44.5	44.46	44.43	44.39	44.36	44.32
84.0	44.51	44.48	44.44	44.41	44.37	44.34
86.0	44.52	44.49	44.46	44.42	44.39	44.36
88.0	44.53	44.5	44.47	44.44	44.4	44.37
90.0	44.55	44.51	44.48	44.45	44.42	44.39

Equation (1.1) suggests that throwers should ensure that the release height is as high as possible. However, the maximum release height attainable by a thrower is restricted by anatomical constraints (Bartonietz, 2000; Dapena, 1984). If the height of release is too high, it can compromise a thrower's ability to apply an accelerating force to the hammer which in turn can cause reductions in the release speed (Bartonietz et al. 1988). In the hammer throw, the ideal release height is approximately shoulder height (Bartonietz, 2000; Bartonietz, Barclay & Gathercole, 1997; Dapena, 1984; Morriss & Bartlett, 1992; Otto, 1991), and to exploit this fact hammer throwers should be tall (Pagani, 1980, Woicik, 1980). Less proficient throwers tend to release the hammer at lower release heights (Bartonietz, 2000).

Once a thrower has developed a technique that allows them to consistently attain optimal values for the release height and release angle it follows, from equation (1.1), that the range can only be increased further through increases to the release velocity (Bartonietz et al. 1988; Dapena, 1984, 1989 1989; Maheras, 2009; Woicik, 1980). It is therefore crucial that the release velocity is as large as possible (Bartonietz, 2000; Dapena, 1984, 1985; Jabs, 1979; Morriss & Bartlett, 1992).

The importance of release velocity in the hammer throw is also highlighted when comparing how changes to the release speed and release angle affect the range. From equation (1.1) it follows that if a thrower releases the hammer from a height of 1.7 m and at an angle of 42° , an increase in release speed from 27 m/s to 28 m/s (3.7% increase) results in a range increase of 5.58 m (7.4%).

However, if the same thrower maintained a release speed of 27 m/s and changed the release angle from 42° to 44° (4.76% increase), this would result in a 0.25 m (0.33%) range increase (Table 2.2). This supports similar work done by Dapena et al. (1982) who reported that a 1% change in the release velocity results in a 2% change in the range of a throw.

Table 2.2. Variation in ranges (in metres) calculated via equation (1.1) using release angles and speeds relevant to the hammer throw. Release height is set at 1.70 m.

← Angle (deg)	Speed (m/s) →					
	25.0	26.0	27.0	28.0	29.0	30.0
40.0	64.70	69.82	75.15	80.67	86.40	92.32
41.0	64.98	70.14	75.49	81.04	86.80	92.76
42.0	65.19	70.37	75.74	81.32	87.10	93.09
43.0	65.33	70.52	75.91	81.50	87.30	93.30
44.0	65.39	70.58	75.99	81.59	87.40	93.41

2.3 Kinematics of the hammer throw

2.3.1 Linear speed development

The speed of the hammer is gradually increased (Figure 2.1) by the thrower as they perform three, four or five 360° turns across the throwing circle, whilst translating in the direction of the throw. The speed of the hammer fluctuates within each turn (Bartonietz, 2000; Bartonietz et al. 1988; Brice et al. 2008; Dapena, 1984; Murofushi et al. 2005; Susanka et al. 1987) with speed increases coinciding closely with the double support phase of each turn, and conversely losses coinciding closely with the single support phase of each turn

(Dapena, 1984, Murofushi et al. 2005). This supports the conclusion from a large amount of literature that indicates that throwers should increase the amount of time spent in double support as this is when the thrower can most effectively accelerate the hammer (Ariel, Walls & Penny, 1980; Bartonietz, 2000; Bartonietz, Barclay and Gathercole, 1997; Gutierrez, Soto & Rojas, 2002; Jaede, 1991; Judge, 2000a; Morley, 2003a; Otto, 1991; Samozvetsov, 1980; Simonyi, 1980).

Whilst increases in speed closely coincide with the double support phase, there is no clear evidence in the literature to suggest that a causal relationship exists between time spent in double support and increase in linear hammer speed (Dapena, 1984, 1985). Therefore, there may be no advantage in lengthening the duration of the double support phases as the true causal factors that contribute to the increase in hammer speed would be left unchanged (Dapena, 1984). This will be discussed further in section 2.4.

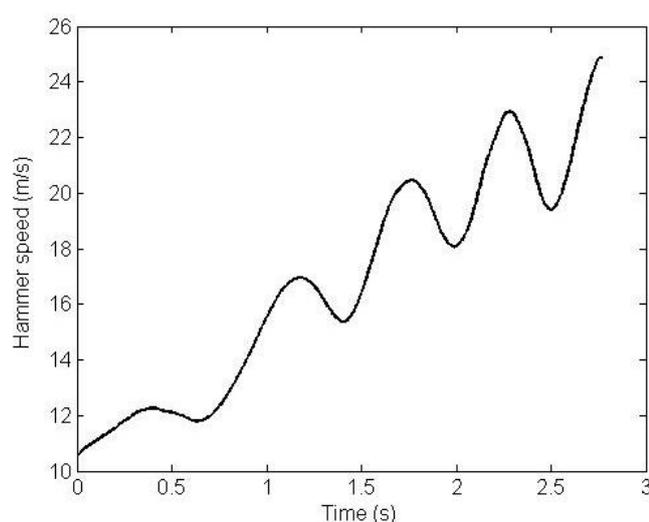


Figure 2.1. Graph of the hammer speed from entry through until release for a typical throw of a four turn thrower (Brice, 2006).

2.3.2 Angular kinematics

Two other kinematic parameters that need to be considered when looking at speed development in the hammer throw are the radius of rotation and the angular speed of the hammer. For the simplistic model of a point mass (m) undergoing circular motion, the linear velocity (v) at any instant is equal to,

$$v = r\omega \quad (2.3)$$

where r is the radius of rotation (distance between the point mass and the axis of rotation) and ω is the angular velocity of the point mass. This relationship suggests that increases in both the radius of rotation and angular velocity will result in an increase in the linear velocity of the rotating point mass. This supports previous work where it has been suggested throwers should ensure that the radius of rotation is as large as possible as this results the hammer velocity being higher (Bartonietz et al. 1988; Morriss & Bartlett, 1992). A larger radius of rotation also results in a greater distance over which to accelerate the hammer however, altering the radius of rotation will cause changes to the inertial resistance of the hammer. For a point mass rotating a distant r from a centre of rotation, the magnitude of the inertial resistance/moment of inertia (I) at any point in time is equal to,

$$I = mr^2 \quad (2.4).$$

From equation (2.4), it is clear that an increase in the radius of rotation will cause the inertial resistance to increase. An increase in the inertial resistance will, in turn, result in a reduction to the angular acceleration (α) and hence angular velocity (provided that the external torque (τ) applied to the mass remains constant). This is due to the following relationship,

$$\alpha = \frac{\tau}{I} \quad (2.5).$$

Therefore, in order to maximise the linear velocity, an optimal relationship between the angular speed and radius of rotation that will also minimise the hammer's inertial resistance needs to be achieved by the thrower.

The typical relationship that exists between the linear speed, angular speed and radius of rotation in the hammer throw is displayed in Figure 2.2. Within each individual turn, increases in linear speed coincide with increases in both the angular speed and radius of rotation (Bartonietz et al. 1988). Over the entire throw, both the linear and angular speeds tend to increase while the radius of rotation decreases slightly (Bartonietz et al. 1988, Dapena & Feltner, 1989).

Having a larger radius in the early parts of the throw has important implications. For a given linear speed, a larger radius allows the hammer-thrower system to rotate with a slower angular velocity (Dapena & Feltner, 1989; Dapena & McDonald, 1989, Maroński, 1991). A slower rate of rotation permits slower contractions of the muscles involved (Dapena & Feltner, 1989; Dapena & McDonald, 1989) which allows these muscles to exert larger forces. This is due to the force-velocity relationship for skeletal muscle (Hill, 1922). In turn, a larger muscle force results in a larger torque and an increase in the overall angular momentum of the system. Therefore, utilising a longer radius in the early parts of the throw facilitates an increase in the angular momentum of the system (Dapena & Feltner, 1989; Dapena & McDonald, 1989).

As the throw progresses, the decreasing trend of the radius of rotation leads to a reduction in the moment of inertia (equation (2.4)) and an increase in the angular acceleration (equation (2.5)). Therefore, a shortening of the radius, particularly in the last part of the final turn, could be utilised by throwers to facilitate an increase in hammer speed prior to release (Dapena & Feltner, 1989; Maroński, 1991).

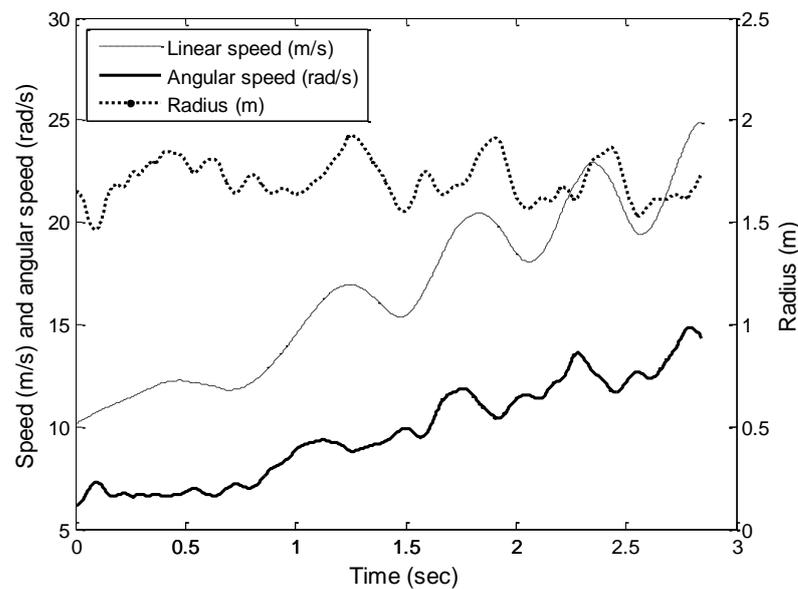


Figure 2.2. Graph of the linear speed, angular hammer speed and the radius of rotation from entry through to release for a typical throw of a four turn thrower (Brice 2006).

The mechanism for increasing or decreasing the radius of rotation involves posture adjustments at the hip and shoulders during the course of the turns (Dapena & Feltner 1989; Dapena & McDonald 1989). Dapena and McDonald (1989) analysed the body positioning and radius of rotation for two throws of eight highly skilled throwers and observed that throwers utilised two different countering techniques: a shoulder countering technique or a hip countering

technique. Throwers who countered with their shoulders had their hips forward and their shoulders further back (Figure 2.3a), while throwers who countered with their hips had their shoulders forward and their hips further back (Figure 2.3b). Throwers that countered with their shoulders tended to do so for the entirety of their throw, while throwers who countered with their hips in the early parts of their throws tended to slowly tilt their thorax back resulting in a shoulder countering position as the throw progressed.

Analyses of the radius of rotation of throwers who used a combination of the two countering techniques found that the hip countering technique resulted in a longer radius of the hammer path in the early turns of the throwers who adopted it (Dapena & McDonald, 1989). A longer radius in the early parts of the throw could give the thrower a mechanical advantage over those who countered with their shoulders as this results in slower rotation of the system and allows the muscles involved to exert larger forces (Dapena & Feltner, 1989; Dapena & McDonald, 1989). As these throwers slowly tilt their thorax backwards, the radius of rotation shortens which could result in an increase in the linear speed.

The optimal technique would be the hip countering technique, due to mechanical advantage it offers, followed by a rapid shortening of the radius of rotation in the final part of the last turn (Dapena & McDonald, 1989). However, it appears that the hip countering technique cannot be maintained in the latter turns of the throw. Dapena and McDonald (1989) proposed two possible theories to explain why throwers could not maintain a hip countering position for the majority of the throw. The first being the increased shear stress placed on

the spine in the hip countering position as a result of having the thorax tilted further forwards. The second being insufficient strength in the shoulder musculature to hold the hammer in a plane that is lower which is a result of being in a hip countering position. Dapena and McDonald (1989) hypothesised that if spinal stress was the limiting factor then it may be unfeasible for a thrower to utilise a hip countering technique for the majority of the throw. However, if shoulder musculature strength was the limiting factor then strengthening of the muscles in this region could assist the thrower to counter with their hips in the late stages of the throw.

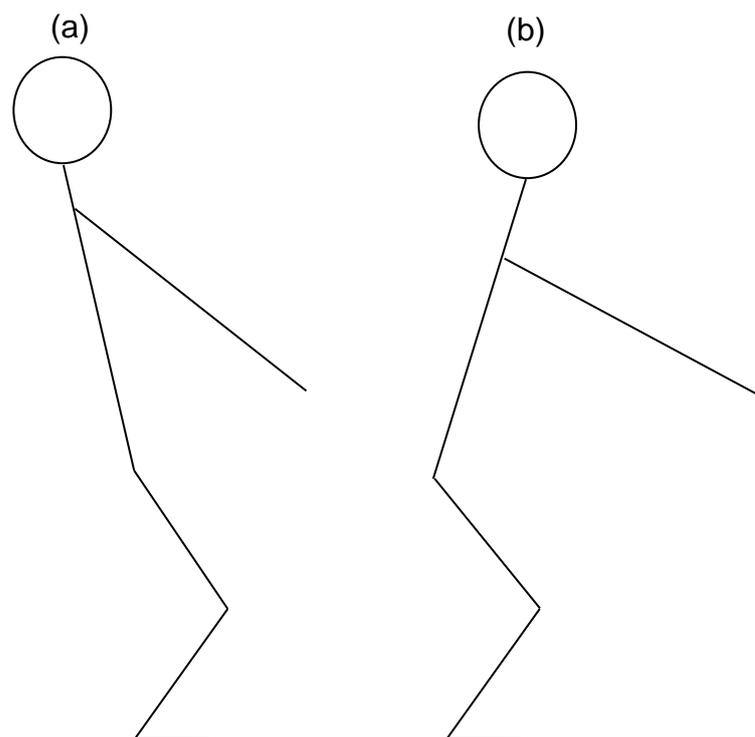


Figure 2.3. Body positions during the double support phase for the two different throwing techniques described by Dapena and McDonald (1989) where throwers (a) counter with their shoulders and (b) counter with their hips.

2.3.3 Mechanics of the hammer, thrower and hammer-thrower systems

Within each turn, the thrower should ensure they utilise a technique that results in a good increase in hammer speed whilst also allowing them to end the turn in such a position that they can further increase the speed in the subsequent turn (Dapena, 1986; Dapena & Feltner, 1989). Having an understanding of the mechanics associated with this should allow athletes and coaches to identify technique problems that limit performance (Dapena, 1986). The mechanics of the hammer throw are complex as the movement involves rotations of the hammer in varying planes, coupled with the translation and rotation of the thrower across the throwing circle (Brice et al. 2008). One way to simplify analyses of the mechanics of the throw is to analyse the vertical and horizontal components of the motion separately (Dapena, 1986). Dapena (1986) utilised this analysis strategy in his investigative study into the mechanics of the hammer throw where the vertical and horizontal motions of the centres of mass of the thrower, hammer and hammer-thrower system were analysed for eight highly skilled throwers.

Dapena (1986) found that the vertical displacements of the centres of mass followed cyclical patterns with a single fluctuation occurring within each turn. For the thrower and the hammer, the timing of the fluctuations were out of sync. The exact reason for the asynchrony is unknown. However, one implication is that for much of the single support phase the centre of mass of the thrower drops while at the same instance the hammer passes through its highest point. The lowering of the body's centre of mass is a result of throwers lowering their hips

and is necessary to maintain high velocity during the turns (Otto, 1991). This also counteracts the pull of the hammer with a low position of the knees (Otto, 1991). Another result of the asynchrony is that the local maxima and minima of the system's centre of mass occurred between those of the thrower and hammer centres of mass. This results in the low points of the system's centre of mass coinciding with the middle of double support, while the high points coincide with the middle of single support (Dapena, 1986). The implications of this are discussed in section 2.4.3.

The horizontal displacement of the centres of mass of the hammer, thrower and hammer-thrower system follow paths that are trochoid in nature (Dapena, 1986). These trajectories are a result of the combination of rotational and translational motion exhibited by the hammer, thrower and hammer-thrower system during the hammer throw. In the case of the hammer, the tangential velocity associated with the rotational motion is much greater than the translational velocity which results in the hammer following a trochoid described as prolate cycloid (Braddock & Van Den Driessche, 1976). The linear velocity vectors of the thrower associated with the rotation and translation are much closer in magnitude resulting in a trochoid path described as cycloid (Braddock & Van Den Driessche, 1976). While for the hammer-thrower system, the rotational velocity is either equal to or less than the translational velocity which results in a near straight path or a trochoid described as curtate cycloid (Braddock & Van Den Driessche, 1976).

It is also important for athletes and coaches to understand how individual movements of the thrower affect the overall performance. Both movement of the trunk and the position of the hammer in relation to the shoulder axis strongly influence hammer throw technique (Morley, 2003a; Otto, 1991). It is widely accepted that the magnitude of the angle between the shoulders and pelvis (shoulder-pelvis separation angle) increases during single support and decreases during double support as the thrower accelerates the hammer (Morriss & Bartlett, 1995a, 1995b; Otto, 1991). While movement of the trunk or shoulders relative to the pelvis has been discussed in coaching literature, it has received little research attention (Judge, Hunter & Gilreath, 2008). Shoulder-pelvis separation angle is discussed further in chapter 5.

2.4 Kinetics of the hammer throw

2.4.2 Forces acting on the hammer

If aerodynamic forces are ignored, the forces acting on the hammer prior to release are gravity (weight) and the force applied by the thrower to the hammer via the hammer's cable (cable force) (Brice et al. 2008; Dapena, 1984). Like hammer velocity, the cable force increases throughout the throw with a single fluctuation occurring within each turn (Figure 2.4) (Bartonietz et al. 1988; Brice et al. 2008; Dapena, 1984; Hwang & Adrian, 1984; Murofushi et al. 2005; Murofushi et al. 2007). The peaks in cable force coincide with minimum vertical hammer displacement whilst troughs coincide with maximum vertical hammer displacement (Brice et al. 2008). This pattern of force development suggests

that throwers actively apply force to the hammer as it travels from its highest to lowest points (Bartonietz, 2000; Brice et al. 2008; Hwang & Adrian, 1984). By doing this, throwers are also utilising the effect of gravity whilst actively accelerating the hammer (Brice et al. 2008; Dapena, 1984).

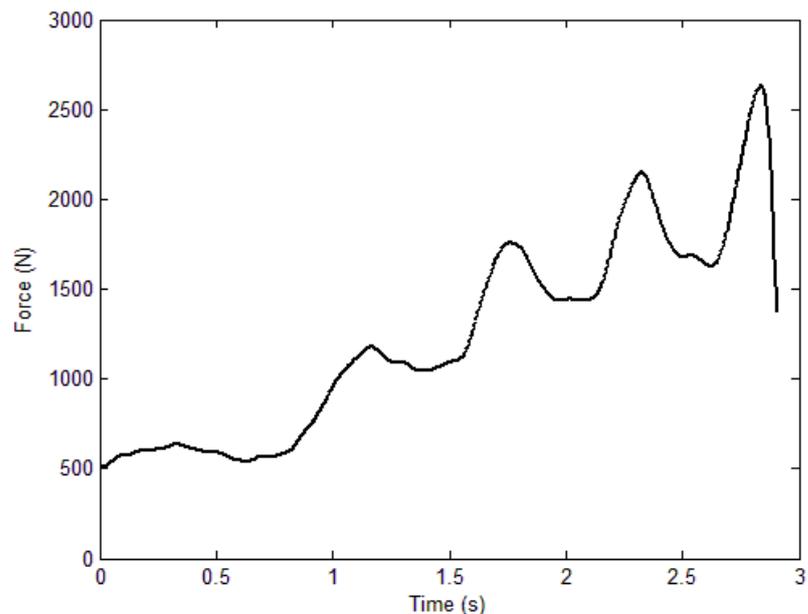


Figure 2.4. Graph of the cable force from entry through until release for a typical throw of a four turn thrower (Brice, 2006).

There are a number of factors that affect the magnitude of the cable force including throwing ability, gender and overall strength of the thrower. The magnitude may also be affected by the thrower's body mass (Okamoto, Sakurai & Ikegami, 2006). Throwers who have a larger body mass will tend to have more muscle volume. This, in turn, provides them with a mechanical advantage as these throwers may be capable of generating a larger cable force (Okamoto, Sakurai & Ikegami, 2006). In addition, leg strength is also an important factor in cable force generation as the leg muscles are responsible for generating the

force, while the trunk and the arms are responsible for transmitting the forces to the hammer (Bartonietz, 2000).

At any instant, the weight and cable force can be decomposed into three components (Figure 2.5); normal, radial and tangential to the instantaneous circle of rotation (Dapena, 1984; Tutevich, 1969). The normal components of the weight and cable force are equal and opposite and have no effect on the hammer's linear velocity. The sum of the radial components determines the radial acceleration of the hammer head which in turn determines the radius of curvature (Brice et al. 2008; Dapena, 1984). The only components that directly affect the instantaneous linear hammer speed are the tangential components of the weight and cable force (Dapena, 1984).

The tangential component of the cable force acts in either the same or opposite direction to the linear hammer velocity, depending on whether the cable force is acting at an angle in front of or behind the direction of the radius of rotation of the hammer's head (Dapena, 1984; Susanka et al. 1987). When acting in the same direction as the linear velocity, it contributes to an increase in the hammer speed; whilst when it acts in the opposite direction it will tend to decrease the hammer speed (Dapena, 1984, 1986). The tangential component of the weight increases the speed of the hammer as it travels from the point of maximum vertical displacement to its lowest point. Conversely, the tangential component of the weight decreases speed as the hammer travels from its lowest point to its highest point within each turn (Dapena, 1984).

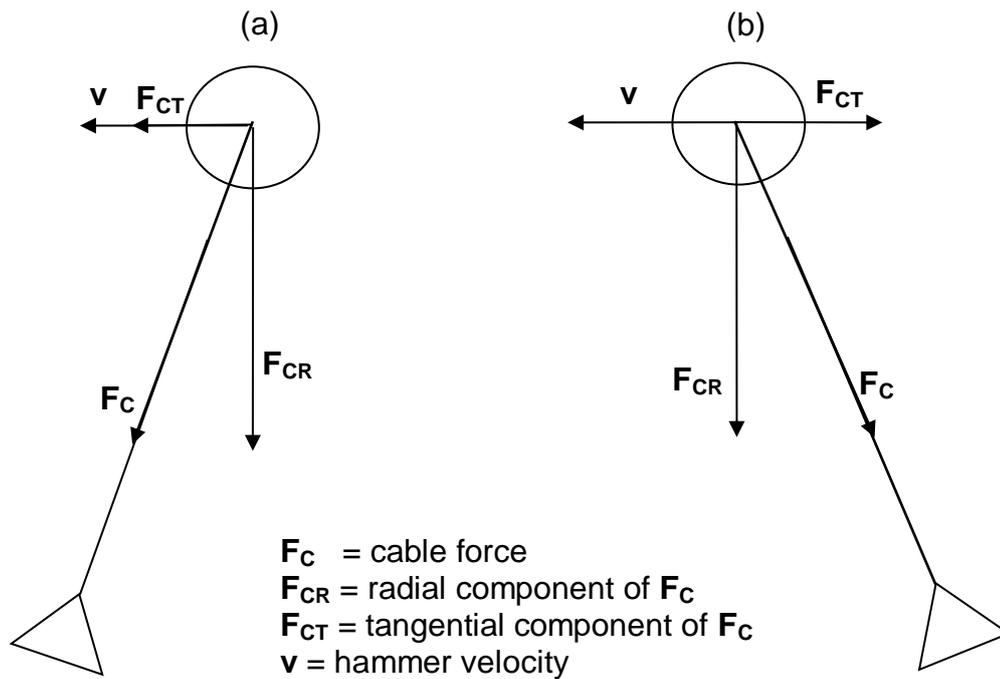


Figure 2.5. Radial and tangential components of the cable force when the cable force vector is pulling in front of the direction of the radius of rotation (a) and when pulling behind (b). The normal component acts perpendicular to the plane of motion in both (a) and (b) and always points upwards as the normal component of the gravity vector always acts downwards.

The effect of cable force and gravity on linear speed development has been discussed at length in the literature, specifically whether these forces are the causal factors for the fluctuations in the hammer's linear speed. As was stated above, gravity contributes to increases in speed as the hammer travels from high to low and decreases when it travels from low to high. This could lead to speculation that gravity may be the causal factor for the speed fluctuations (Dapena, 1984, 1985). Dapena (1984, 1985) found that although gravity contributed to the fluctuations in the speed profile, the fluctuations were still clearly present when the effect of gravity was removed.

Dapena and Feltner (1989) performed a more detailed investigation into the causal factors of speed fluctuations in the hammer throw and found in many cases the effects of gravity and horizontal translation of the hammer-thrower system were responsible for the speed fluctuations. In instances where gravity and translation only accounted for part of the fluctuation, the remainder of the fluctuation was due to the cable force pulling either in front of or behind the centroid of the hammer head. In other words, the tangential component of the cable force is the causal factor for fluctuations in linear hammer speed in these instances. The tangential component of the cable force and its contribution to linear hammer speed is discussed further in Chapter 4.

2.4.2 Forces acting on the thrower

The motions of the thrower's centre of mass are affected by three forces; gravity, a reaction force exerted by the ground on the thrower's feet (ground reaction force) and a reaction force equal and opposite to the cable force (cable reaction force) (Dapena, 1986; Dapena & Feltner, 1989). For a good throw, the thrower must achieve an appropriate combination of hammer and ground forces that will produce a good increase in hammer speed (Dapena & Feltner, 1989). Direct measurement or calculation of the cable force (and hence the cable reaction force) is relatively easy, and such data has been reported numerous times in the literature (Bartonietz et al. 1988; Brice et al. 2008; Hwang & Adrian, 1984; Murofushi et al. 2005; Murofushi et al. 2007). Conversely, a limited number of studies detailing the ground reaction force in the hammer throw have

been reported, presumably due to the difficulties associated with collection of accurate data for such a complex movement.

As the throw progresses, the magnitude of the cable reaction force gradually increases, while the average ground reaction force remains roughly constant for the duration, the exception being the delivery phase when the average force is larger than in the preceding turns (Murofushi et al. 2007). The vertical component of the ground reaction force is the largest component and is greater than body weight for the majority of the double support phase (Murofushi et al. 2007). The horizontal components of the ground reaction force are less than body weight for the entire throw and have periods where they are both negative and positive (Murofushi et al. 2007). The influence that these forces have on the thrower's centre of mass can be better understood if the horizontal and vertical components are analysed separately.

The combined effect of gravity, the vertical component of the ground reaction force and the vertical component of the cable reaction force results in a cyclical pattern for the displacement of the thrower's centre of mass that was previously described in section 2.3.3 (Dapena, 1986). When the vertical displacement of the thrower's centre of mass is increasing, the sum of the vertical components of the ground and cable reaction forces is greater than the body weight of the thrower. Conversely, when the displacement is decreasing, the sum of the vertical components of the ground and cable reaction forces is less than body weight.

The combined effect of the horizontal components of the ground reaction force and horizontal component of the cable reaction force results in thrower's centre of mass following a cycloid path (Dapena, 1986). As has already been discussed in section 2.3.3, the horizontal components of the ground reaction force are small, while the horizontal component of the cable reaction force is much larger. Therefore, there is a resultant horizontal force acting on the thrower in the direction of the cable reaction force (Dapena, 1986). This force does not cause the thrower to translate forwards but rather provides a centripetal acceleration that keeps the thrower rotating in a roughly circular path about the centre of mass of the hammer-thrower system (Dapena, 1986).

2.4.3 Forces acting on the hammer-thrower system

The motions of the centre of mass of the hammer-thrower system are only influenced by gravity and the ground reaction force since the cable force and cable reaction force are equal and opposite (Dapena, 1986). The ground reaction force will influence both the vertical and horizontal components of the centre of mass' motion while gravity will only influence the vertical motion.

Like the centre of mass of the hammer and the thrower, the combined effect of the forces acting in the vertical direction results in a cyclical pattern for the displacement of the centre of mass of the hammer-thrower system (Dapena, 1986). In section 2.3.3, it was pointed out that the vertical displacement of the system was at its minimum when the thrower was in double support phase (Dapena, 1986). When the system's centre of mass is at its lowest point, the

vertical ground reaction force is greater than the weight of the system and results in a positive acceleration of the system's centre of mass. The ground reaction force is at its largest at this point, and the fact this coincides with the double support phase means that the thrower is in the most stable position when this force is at its largest. The opposite occurs when the system's centre of mass is at its highest point; the ground reaction force is less than the weight of the system which results in a vertical deceleration of the system's centre of mass during single support.

The horizontal motion of the centre of mass of the hammer-thrower system follows a near straight path or curtate cycloid (Dapena, 1986). Dapena (1986) hypothesised that this is an indication that the horizontal components of the ground reaction force, responsible for the horizontal motion of the hammer-thrower system, are small. This is supported by the data presented by Murofushi et al. (2007) that shows that the magnitudes of the horizontal components of the ground reaction force are small when compared to the magnitudes of the other forces acting in the hammer throw.

Chapter 3 – Data acquisition

3.1 Introduction

Data reported in this thesis were collected during three, field-based data collection sessions. This chapter outlines the details of data acquisition procedures and the modelling and data processing protocols that were utilised. Specific details associated with each individual study can be found in each related chapter.

3.2 Experimental overview

Ten hammer throwers (five male and five female) participated in the studies detailed in this thesis. All data collection was undertaken at the Australian Institute of Sport (AIS) Athletics facility. This is a surveyed, outdoor facility which meant that the participants were able to perform a throw that could also be correctly measured for distance thrown. All participants gave written informed consent to participate in the data collection for the studies outlined in this thesis, which were all given ethical approval by the James Cook University (JCU) Human Ethics Committee and the AIS Ethics Committee (see Appendix A for Participant Information Sheet and Informed Consent Form).

Prior to data collection, each participant was allowed to complete their usual warm up. Participants were then asked to complete ten throws using a hammer that was instrumented with a single general purpose strain gauge which directly measured the cable force throughout each throw. In addition, three-dimensional positional data of retro-reflective markers located on both the hammer's cable and anatomical landmarks of the participant were also collected. From these data, a number of kinematic and kinetic variables for the hammer and thrower were calculated.

3.3 Participant description

Five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) Australian hammer throwers of varying handedness and ability participated in this study (Table 3.1). Of the ten participants, two used a three turn style, seven used a four turn style and one used a five turn style. All but one participant (participant 5) competed in the 2008 final at the Australian National Track and Field Championships with all three male and female placegetters being part of this cohort. Each participant was in the competition phase of the Australian domestic athletics season at the time of data collection.

Table 3.1. Gender, handedness, mass, height and number of turns used by each athlete who participated in the studies of this thesis.

Participant number	Gender	Handedness	Mass (kg)	Height (m)	Number of turns
1	M	Right	108.10	1.91	3
2	M	Left	110.56	1.91	4
3	M	Right	110.22	1.93	4
4	M	Right	102.42	1.88	3
5	M	Right	99.86	1.79	4
6	F	Right	131.70	1.78	4
7	F	Right	90.00	1.68	4
8	F	Left	113.76	1.69	4
9	F	Left	79.46	1.67	4
10	F	Right	93.08	1.64	5

3.4 Data acquisition procedures

3.4.1 Three-dimensional positional data acquisition

Each participant had retro-reflective markers (15 mm in diameter) positioned on their skin over anatomical landmarks (Table 3.2 and Figure 3.1) in accordance with the Plug-In Gait (PIG) marker protocol (Davis III et al. 1991). Markers were also located on the cable for each hammer at known distances from the hammer's head. The three-dimensional coordinate data for all markers were recorded using a 21 infra-red camera Vicon system (Oxford Metrics, Oxford, UK), sampling at a frame rate of 250 Hz. Testing was conducted at an outdoor facility, and all data collection took place after twilight conditions. Low light conditions were necessary as the infra-red cameras required minimal light to operate effectively. The cameras were positioned around the hammer throw circle at varying positions and heights (Figure 3.2) to ensure that the markers could be seen at all times.

For safety reasons, the throwing circle was positioned such that it had protective netting surrounding the rear and sides of the throwing circle (Figure 3.2). This meant that a number of the cameras were positioned behind this protective netting. Following a number of pilot testing sessions, it was found that this had minimal impact on data collection due to the high number of cameras that were utilized in this study.

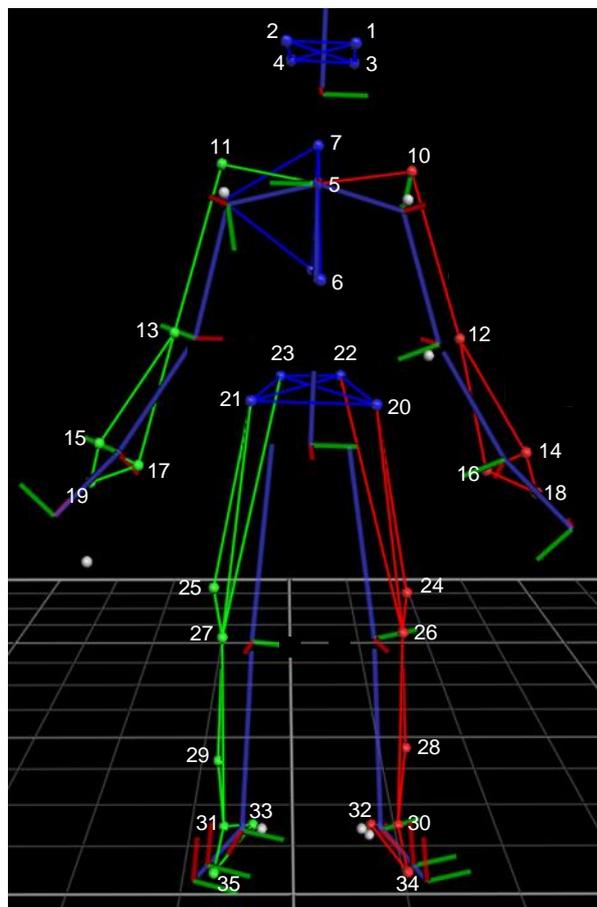


Figure 3.1. Plug-In Gait marker placement.

Table 3.2. Plug-In Gait model marker names and marker location definitions.

*number of the markers displayed in Figure 3.1.

Segment	Number*	Label	Description	Definition
Head	1	LFHD	Left front head	Approximately over the temple
	2	RFHD	Right front head	Approximately over the temple
	3	LBHD	Left back head	Back of head in line with LFHD
	4	RBHD	Right back head	Back of head in line with RFHD
Thorax	5	CLAV	Clavicle	Sterno-clavicular notch
	6	STRN	Sternum	Xiphoid process
	7	C7	C7 vertebra	Spinous process
	8	T10	T10 vertebra	Spinous process
	9	LBAK	Left back	Mid scapula
Arm	10	LSHO	Left shoulder	Acromio-clavicular joint
	11	RSHO	Right Shoulder	Acromio-clavicular joint
	12	LELB	Left elbow	Lateral epicondyle
	13	RELB	Right elbow	Lateral epicondyle
	14	LWRA	Left wrist	Metacarpal 1 side
	15	RWRA	Right wrist	Metacarpal 1 side
	16	LWRB	Left wrist	Metacarpal 5 side
	17	RWRB	Right wrist	Metacarpal 5 side
	18	LFIN	Left finger	Base of metacarpal 2
	19	RFIN	Right finger	Base of metacarpal 2
Pelvis	20	LASI	Left ASIS	Anterior superior iliac spine
	21	RASI	Right ASIS	Anterior superior iliac spine
	22	LPSI	Left PSIS	Posterior superior iliac spine
	23	RPSI	Right PSIS	Posterior superior iliac spine
Leg	24	LTHI	Left thigh	In line with the knee and hip joint centres
	25	RTHI	Right thigh	In line with the knee and hip joint centres
	26	LKNE	Left knee	Knee joint axis (lateral aspect)
	27	RKNE	Right knee	Knee joint axis (lateral aspect)
	28	LTIB	Tibia	In line with the ankle and knee joint centres
	29	RTIB	Tibia	In line with the ankle and knee joint centres
	30	LANK	Left ankle	Lateral malleolus
	31	RANK	Right ankle	Lateral malleolus
	32	LHEE	Left heel	Calcaneous in line with toe marker
	33	RHEE	Right heel	Calcaneous in line with toe marker
	34	LTOE	Left toe	Head of metatarsal 2
	35	RTOE	Right toe	Head of metatarsal 2

The strobe intensities and light thresholds for each of the cameras were adjusted within the Vicon Nexus software suite (Oxford Metrics, Oxford, UK) to remove the effect of light reflecting off surfaces such as the metal poles of the hammer cage. Once appropriate thresholds and intensities were chosen, the volume where the hammer throw activity took place was dynamically calibrated using the calibration functions in the Vicon Nexus software suite. Following the dynamic calibration, the image error of each camera was assessed. If the image

error for each camera was below 0.25 (in line with the AIS Biomechanics Protocols (Dowlan, 2003)), it was deemed to be an adequate calibration. Once the calibration was complete, the origin was set approximately at the centre of the throwing circle with the y -axis aligned with the direction of the throw, the z -axis defined as being in the vertical direction and the x -axis defined as being perpendicular to the y - and z -axes (Figure 3.3).

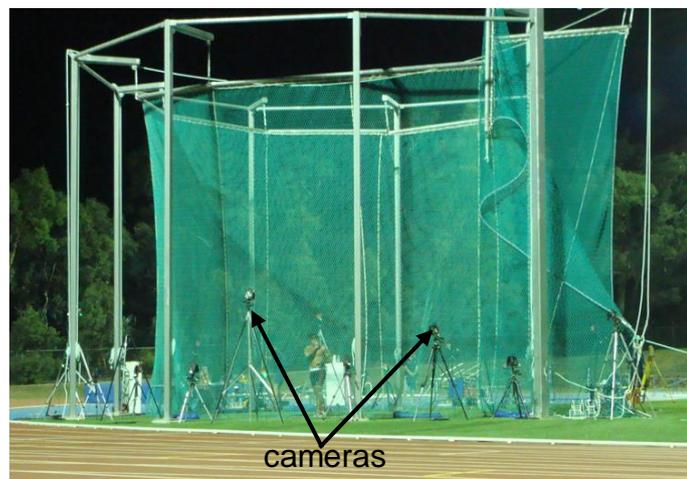


Figure 3.2. Field testing area. Throw direction is from left to right.

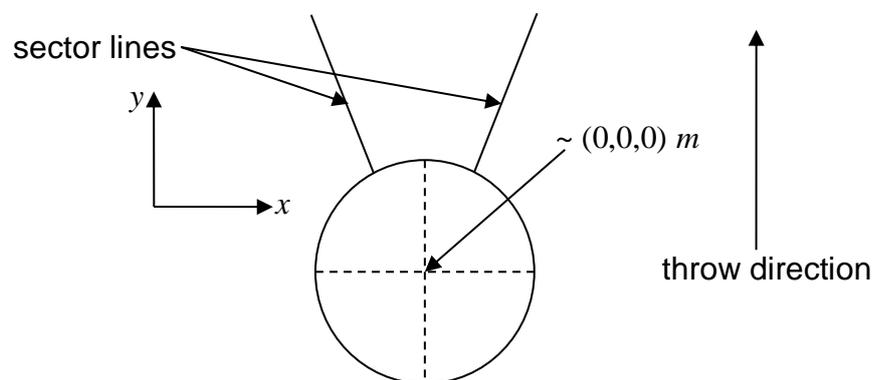


Figure 3.3. Global reference frame used in each of the studies of this thesis. The z -axis is perpendicular to the ground and the origin was located roughly at the centre of the throwing circle.

Prior to data collection, a number of anthropometric variables were measured for each participant. A description of these variables and how they were measured is reported in Table 3.3. These measures were required for post-processing purposes within the Vicon Nexus software suite.

After the participants had carried out their standard pre-training warm up, they were required to perform a static trial before commencing their ten throws. For the static trial, the participant stood stationary at the centre of the throwing circle, in the anatomical position. The three-dimensional coordinate data of the retro-reflective markers located on the participant's body were recorded in this position for an arbitrary amount of time (only a single frame of footage was required). The static trial was later used along with the specific anthropometric measures, described in Table 3.3, to determine the locations of the participant's joint centres relative to the retro-reflective markers throughout each of their throws.

Each participant then proceeded to complete ten throws (dynamic trials) where the aim of each throw was to throw the hammer as far as possible without committing a foul. The three-dimensional coordinates of the markers located on both the participant and the hammer's cable were recorded. Participants were allowed to have a rest period between each throw to mimic competition-like conditions during which the distance of each throw was measured in accordance with the IAAF competition protocols (IAAF, 2010).

Table 3.3. Description of specific anatomical measurements required for the
 Plug-In Gait model.

Subject measurement	Measurement description
Mass	Mass of subject (in kg)
Height	Height of subject
Inter-ASIS distance	Distance between LASI and RASI markers
Leg length	Distance between ASIS and medial malleolus
Knee width	Knee width about flexion axis
Ankle width	Ankle width about flexion axis
Shoulder offset	Vertical distance from SHO marker to glenohumeral joint
Elbow width	Distance between the medial and lateral epicondyles
Wrist thickness	Distance between ulna and radial styloids
Hand thickness	Distance between dorsal and palmar surfaces

3.4.2 Cable force direct measurement procedures

The participants performed each throw with a hammer that had a single, general purpose strain gauge positioned on the cable. Prior to each throw, the strain gauge device was calibrated using a custom designed calibration rig (Figure 3.4). The rig consisted of two Enerpac hydraulic rams (Actulant, Butler, USA) connected to two arms, a force link (Kistler, Amherst, USA) and a force link amplifier (Kistler, Amherst, USA). Each cable was mounted in the rig, in series with the force link. The hydraulic rams were used to push the arms of the rig outwards resulting in the application of a tensile force to the hammer cable. This tensile force was simultaneously measured via the strain gauge and the force link. A data-logger, sampling at 500 Hz, recorded the data output from the strain gauge and the force link voltages that were output from the force link amplifier. Once calibrated, the cable was removed from the rig and a hammer head and handle were attached to either end such that the total mass of the hammer system was 7.26 kg for males and 4 kg for females (competition standards).

The data-logger used for the calibration procedure was positioned on a Velcro strap that ran around the participant's thorax. This strap was positioned so that none of the retro-reflective markers were occluded. Prior to each throw, the strain gauge device located on the cable was connected by a thin wire to the data logger. This wire passed up the participant's arm and down their back to the logger. The wire was fastened in such a manner that it did not interfere with the participant's throwing technique and was designed to disconnect at a small connector located at the wrist as the hammer was released.

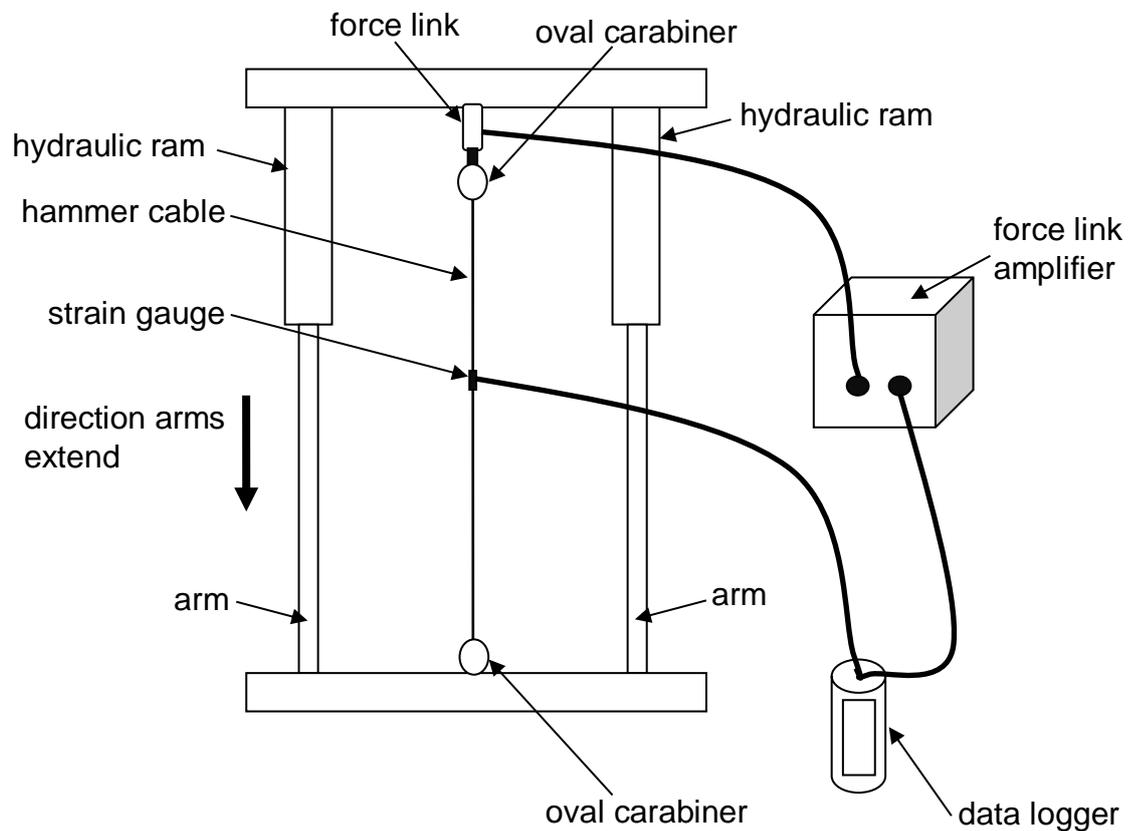


Figure 3.4. Strain gauge calibration rig. Note: the hammer ball and handle were detached from the cable throughout the calibration procedure.

3.5 Data processing procedures

3.5.1 Three-dimensional data processing procedures

All video footage was post processed in the Vicon Nexus software suite. The first step of the processing procedure was to model each of the participant's static trials using the PIG static modelling function. Before the static model could be run, each retro-reflective marker was named using the labels listed in Table 3.2, and the anthropometric measures listed in Table 3.3 were entered into the Subject Parameter section. Once this was complete, the PIG static model was executed using the static marker positions and the anthropometric measures. This determined the locations of the participant's joint centres relative to the retro-reflective markers located on the skin surface.

Once processing of the static trial was complete, the dynamic trials were processed. Each marker was again named (this time including the additional two markers located on the hammer's cable), and any gaps in the marker trajectories were filled using either a pattern fit or spline fit. If the gaps in the trajectories of the markers that made up the head, thorax or pelvis segments were too large to fill in this manner, then a model was run in Vicon Nexus that replaced the missing marker. This model replaced the missing marker in the dynamic trial by using the positions of the other three markers that made up the segment and the relative positions of all four markers during the static trial. The trial was discarded if more than one marker for any of these segments was missing as the gap in the marker trajectory could not be filled.

The three-dimensional data were then filtered using a Woltring (spline) filter with the mean standard error (MSE) set at 15. This was found to be the optimal filter level for this data set following a Fourier and Residual analysis (Winter, 2009). The dynamic PIG model was then run for each dynamic trial, and certain kinematic variables were output by the model at this time. Details of the variables that were output are discussed further in Chapter 5.

3.5.2 Measured force data processing procedures.

All strain gauge data recorded by the data-logger were in analogue-digital (A-D) units. Before this raw data could be used, it was converted to Newtons. This was done by using the strain gauge and force link calibration files that were recorded by the data-logger during the calibration procedure outlined in section 3.4.2. Each calibration file was used to determine the linear relationship between strain gauge A-D units and force for each strain gauge device. The strain gauge and force link data files were used to perform a linear regression within the Matlab software suite (The Mathworks, Natick, USA). The resultant linear regressions were used to convert the raw strain gauge data, collected during each throw, into force.

These converted, measured force data were later used to derive and validate a method that allowed linear hammer speed to be determined from directly measured force data in the training environment. Specifics of that study are described in Chapter 6.

3.5.3 Hammer head position calculation procedures

All three studies presented in this thesis required information about the three-dimensional position of the hammer's head throughout each throw. Its position in the global reference frame was determined using the positions of the retro-reflective markers located on the hammer's cable and the directional cosines of a vector that passed between the two markers.

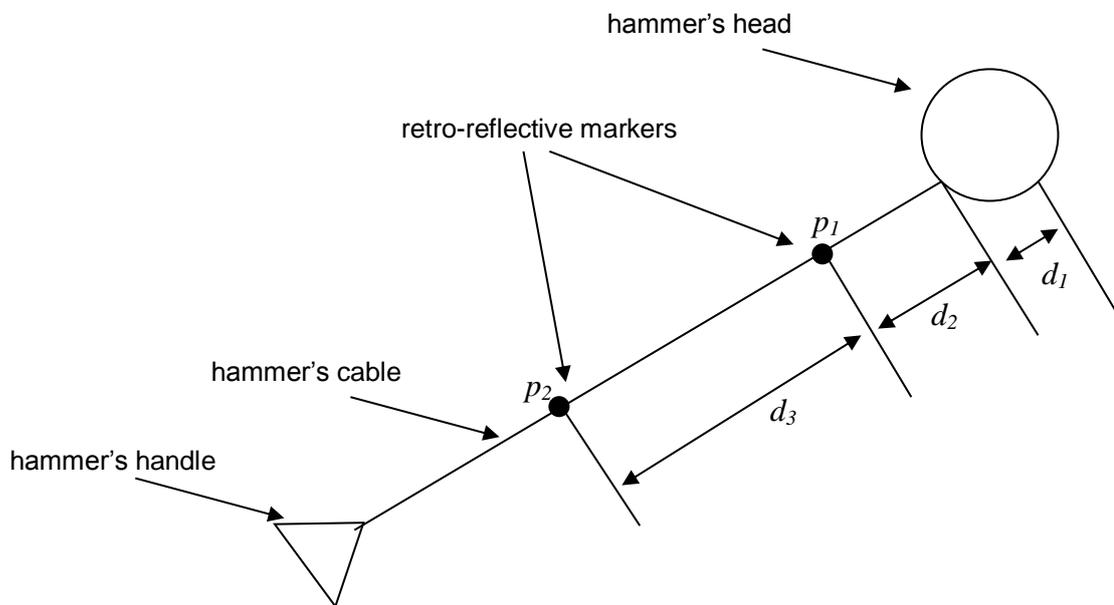


Figure 3.5. Retro-reflective markers positioned on the hammer's cable at points $p_1 = (x_1, y_1, z_1)$ and $p_2 = (x_2, y_2, z_2)$. d_1 is the radius of the hammer's head (varied depending on which hammer head was used), d_2 is the distance between the point closest to the hammer head and the end of the hammer cable ($d_2 = 0.25$ m) and d_3 is the distance between the two points ($d_3 = 0.45$ m).

From Figure 3.5 the following direction cosines apply,

$$\cos \alpha = \frac{x_1 - x_2}{d_3} \quad \cos \beta = \frac{y_1 - y_2}{d_3} \quad \cos \gamma = \frac{z_1 - z_2}{d_3}$$

where α is the angle between the x -axis and the vector that passes between p_1 and p_2 , β is the angle between the y -axis and the vector that passes between p_1 and p_2 and γ is the angle between the z -axis and the angle that passes between p_1 and p_2 .

From above, the x , y and z coordinates of the hammer's head are given by

$$x = (d_2 + d_1) \cos \alpha + x_1 \quad (3.1)$$

$$y = (d_2 + d_1) \cos \beta + y_1 \quad (3.2)$$

$$z = (d_2 + d_1) \cos \gamma + z_1 \quad (3.3)$$

Equations (3.1), (3.2) and (3.3) were used along with the three-dimensional position data of the markers to determine the position of the hammer's head for each throw. These calculations were performed in the Matlab software suite.

Chapter 4 – An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers.

4.1 Chapter Statement

This chapter presents the findings of a study that examined the relationship between the thrower applied cable force and linear hammer speed. The aim here was to quantify what relationship exists between these two parameters and to also assess how the magnitude and direction of the cable force affects the fluctuations in hammer speed.

The information and findings reported in this chapter are adapted from the following journal article:

Brice, S. M., Ness, K. F., & Rosemond, D. (2011). An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers. *Sports Biomechanics*, 10, 174-184. doi:10.1080/14763141.2011.592210

Published version of this article is included in Appendix B.

4.2 Introduction

The projectile nature of the hammer after release and the importance of the speed of the hammer at the point of release have been discussed in depth in the literature and in Chapters 1 and 2 of this thesis. The acceleration of the hammer to its point of release is affected by the forces acting on the hammer and by the time interval that these forces act over. If aerodynamic forces are ignored, the forces acting are gravity and the thrower applied cable force and at any instant, these forces can be decomposed into three components (see Figure 4.1); normal, radial and tangential to the instantaneous circle of rotation (Dapena, 1984; Tutevich, 1969). The only components that directly affect the instantaneous linear hammer speed (hammer speed) are the tangential components of the weight and cable force (Dapena, 1984).

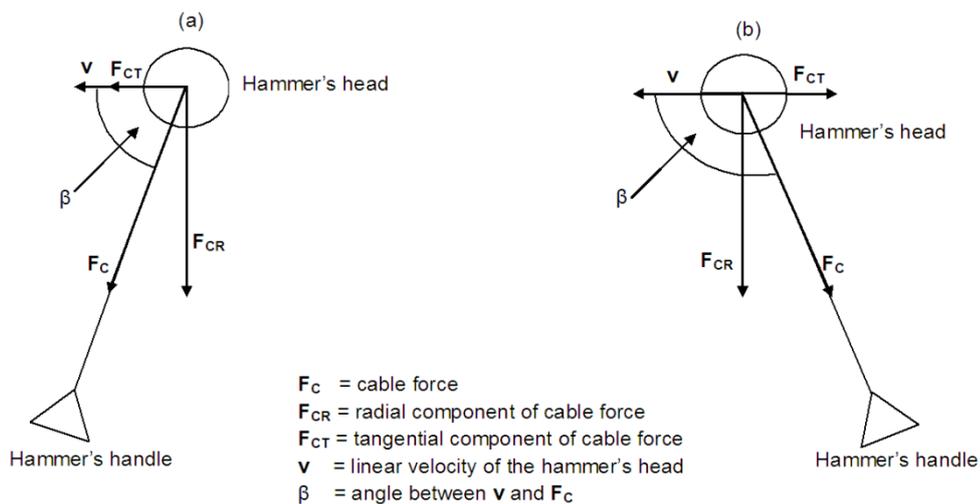


Figure 4.1. Radial and tangential components of the cable force when the cable force vector is pulling in front of the direction of the radius of rotation (a) and when it is pulling behind (b). The normal component acts perpendicular to the plane of motion in both (a) and (b).

The tangential component of the weight increases the speed of the hammer as it travels from the point of maximum vertical displacement to its lowest point. Conversely, the tangential component of the weight decreases speed as the hammer travels from its lowest point to its highest point within each turn (Dapena, 1984). The tangential component of the cable force (tangential force) acts in either the same or opposite direction to the linear hammer velocity, depending on whether the cable force is acting at an angle in front of or behind the direction of the radius of rotation of the hammer's head (Dapena, 1984; Susanka et al. 1987). When acting in the same direction as the linear velocity, it contributes to an increase in the hammer speed; whilst when it acts in the opposite direction it will tend to decrease the hammer speed (Dapena, 1984, 1986). Given this relationship between tangential force and speed development, it is essential that athletes and coaches have a strong understanding of how this force acts during the throw.

Recently, there have been increasing amounts of research into the acceleration mechanism of the hammer (Maheras, 2009; Murofushi et al. 2005; Murofushi et al. 2007; Ohta et al. 2010). While this recent literature has allowed good insight into the acceleration mechanism, there is still little in the literature that specifically investigates the tangential force and its effect on hammer speed. Susanka et al. (1987) found that for a 79.22 m throw by former Soviet hammer thrower Yuriy Sedykh (current world record holder) in the final two turns, the tangential force fluctuates between ± 500 N twice per turn. Another study by Bartonietz (1994) presented data from a 82.34 m throw by the same athlete that showed that throughout the throw, the tangential force fluctuated in polarity

between approximately -150 N and 200 N once per turn. Dapena and Feltner (1989) investigated the influence of the direction of the cable force on fluctuations in hammer speed and found the fluctuations not due to gravity were caused by the positive and negative fluctuations in the tangential force. While Dapena and Feltner (1989) reported this finding, no inferences were made about the strength of this relationship or how this relationship could be used specifically to reduce the size of losses in hammer speed.

The purpose of this cross-sectional investigative study was to quantify the strength of the relationship between cable force and hammer speed and identify how the magnitude and direction of the cable force affects the fluctuations in hammer speed. Specifically, this was to determine which element of the cable force's tangential component is most closely related to losses/gains in hammer speed, given that these losses/gains occur when the polarity of the tangential force is negative/positive. Investigation into how athlete performance can be improved in relation to cable force application was carried out.

4.3 Methods

Five male and five female hammer throwers (described in section 3.3 of this thesis) participated in the study detailed in this chapter. The data collection for this study was carried out at a surveyed outdoor track and field facility, and all throw distances were measured in accordance with the IAAF competition protocols (IAAF, 2013a). Participants were asked to complete ten throws with a competition standard hammer (7.26 kg for males and 4 kg for females) that had

retro-reflective markers positioned on the hammer's cable at known distances from the centre of the hammer's head.

A 21 infra-red camera system sampling at a frame rate of 250 Hz was used to record the three-dimensional position of the markers on the hammer's cable throughout each of the participant's ten throws. The cameras were dynamically calibrated using the procedure outlined in section 3.4.1, and the origin was set approximately at the centre of the throwing circle (Figure 3.3).

The collected video footage of the throws were post processed in Vicon Nexus using the data processing and filtering protocols outlined in section 3.5.1. Once the data were filtered the three-dimensional marker position data were used, along with direction cosines, to determine the position of the hammer's head for each throw from entry through to release (see section 3.5.3 for equation details). Entry was defined as being the point in the throw, just prior to the start of the turns, when the hammer passed through 270° (right handed thrower) or 90° (left handed thrower) where the 0° was aligned with the negative y -axis and 180° was aligned with the positive y -axis. Release was defined as being the instant in time when separation was detectable between the hands and the hammer's handle. This was measured by comparing the distance between markers on the participant's hands and the marker on the hammer's cable that was closest to the hands.

The hammer head positional data were used to determine linear hammer velocity, the cable force and the tangential force (Figure 4.1). The cable force was determined from

$$\mathbf{F}_c = m \left(\frac{d^2 \mathbf{s}}{dt^2} - \mathbf{g} \right) \quad (4.1)$$

where m is the mass of the hammer (7.26 kg for males; 4 kg for females), \mathbf{s} is the three-dimensional position of the hammer's head at any time t and \mathbf{g} is the gravity vector (approximately -9.80 m/s^2 in the vertical direction which is defined as the z direction in this study). The magnitude of the tangential force was calculated using

$$F_{c_T} = F_c \cos \beta \quad (4.2)$$

where β is the angle between the cable force and the linear hammer velocity vectors (see Figure 4.1). The tangential force is positive when $\beta < 90^\circ$ and negative when $\beta > 90^\circ$. All calculations were carried out using the Matlab software suite.

Traces of the calculated kinetic and kinematic parameters, along with the vertical position of the hammer's head were produced for comparison with previously reported data in the literature. This was also done to build an understanding of when certain behavior, such as maxima and minima of the focus variables, were occurring. The magnitude and behaviour of the angle between the hammer velocity vector and the cable force vector (β) in equation 4.2) was also investigated as it, and the magnitude of the cable force, affects the magnitude and direction of the tangential force which in turn is responsible for increases and decreases in hammer speed.

The relationship between the following variables was investigated:

- size of the decreases in speed and:
 - decreases in cable force
 - time spend applying negative tangential force
 - magnitude of tangential force at its most negative
 - magnitude of β at its greatest
 - magnitude of cable force when β is at its greatest
- size of the decreases in both cable force and tangential force
- size of increases in speed and:
 - increases cable force
 - magnitude of tangential force at its most positive
 - magnitude of β at its greatest in the previous single support phase.

Pearsons correlation and the associated p-values (p) measured the strength of these relationships. A relationship was deemed to be significant if $p < 0.05$. All correlations were classified using the definitions described by Hopkins (2006). Scatterplots of the bivariate relationships between each of the correlates were also explored for the effects of outlying observations. All cable force and tangential force data used in the correlation analyses were normalised by dividing by the weight of the hammer that was used so that all male and female data could be combined for analyses. There was a strong emphasis on investigating the relationships between decreases in the variables as the main purpose of this study was to ascertain the cause of losses in hammer speed.

It was expected that analyses of the preceding correlates would assist with identifying how the magnitude and direction of the cable force directly effects hammer speed, particularly losses in hammer speed. This was done to ascertain whether an athlete should alter the magnitude of the cable force or the angle it acts at so as to reduce the detrimental effect the tangential force has on hammer speed when its polarity is negative.

4.4 Results

Averages for each gender in release speed, distance thrown, best distance thrown, peak cable force and peak cable force normalised for hammer weight are shown in Table 4.1. These data give some indication as to the skill level of the participants in this study. The magnitudes of the peaks in normalised cable force are almost the same across genders (Table 4.1), and comparison between peak normalised cable force and distance thrown shows there is a near perfect correlation between the two ($R = 0.94$, $p = < 0.0001$).

Table 4.1. Gender averages of distance thrown, distance of best throw produced, release speed, peak cable force and peak force normalised for hammer weight in this study. Standard deviations indicated in brackets.

Gender	Average throw distance (m)	Best throw (m)	Release speed (m/s)	Peak force (N)	Peak force (normalised)
Male	54.3 (7.6)	57.1 (8.4)	23.7 (1.8)	2399 (292)	33.74 (4.11)
Female	53.9 (3.2)	56.4 (2.3)	24.1 (0.7)	1376 (63.4)	35.12 (1.62)

The hammer speed, cable force, tangential force and vertical position of the hammer's head, for four different participant's best throw, are shown in Figures 4.2, 4.3 and 4.4 respectively. Both hammer speed and cable force increased

throughout each throw with a fluctuation (peak and trough) occurring each turn and just prior to hammer release (Figures 4.2 and 4.3). The tangential force displays periods of both positive and negative values (Figure 4.4). The periods of negative tangential force occur during the early stages of single support with the tangential force being at its most negative around the centre of single support as the hammer approaches its highest point. These periods also coincide with decreasing hammer speed. The troughs in the tangential force became progressively more negative as the throw progressed while generally the peaks remained at approximately the same magnitude.

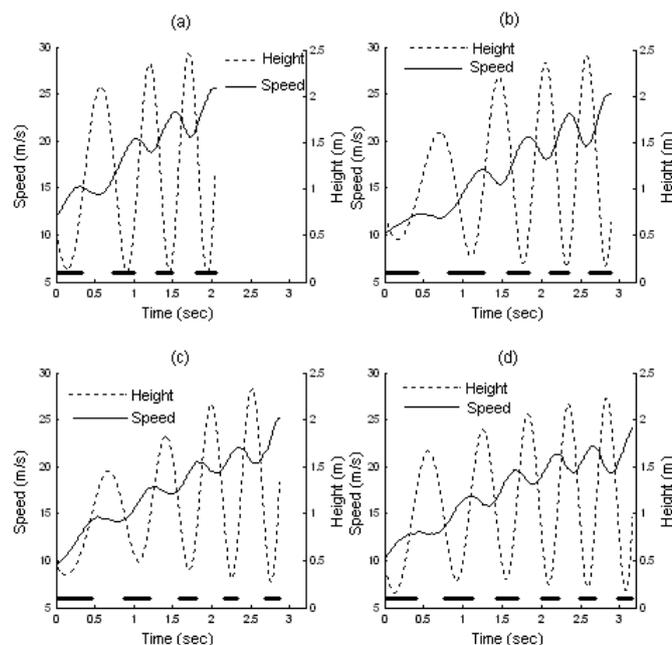


Figure 4.2. Hammer speed and vertical height of the hammer's head from entry through to release for the best throw of: (a) male three turn thrower (63.22 m), (b) male four turn thrower (61.45 m), (c) female four turn thrower (59.86 m) and (d) female five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete is in double support.

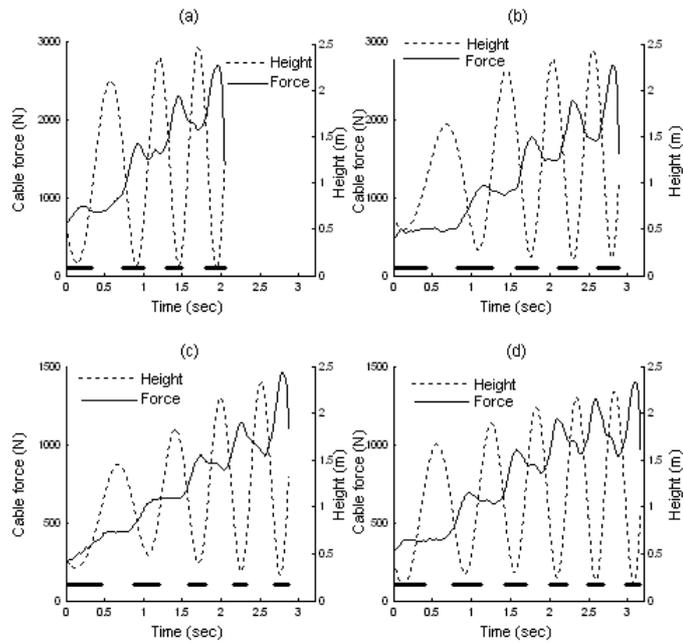


Figure 4.3. Cable force magnitude and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 4.2.

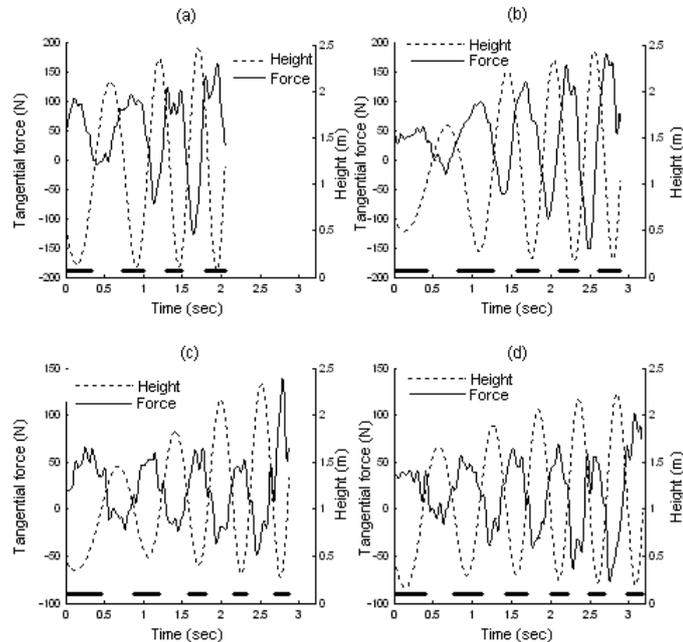


Figure 4.4. Tangential force and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 4.2.

Comparisons between the size of both increases and decreases in cable force and speed were carried out to establish what relationship exists between the two. A strong positive relationship was found to exist between decreases in both speed and cable force ($R = 0.89$, $p < 0.05$, Figure 4.5a). The positive relationship observed between increases in both speed and cable force was weaker than that observed between the decreases ($R = 0.63$, $p < 0.05$, Figure 4.5b). Although this was a weaker relationship, the two were still highly correlated.

A comparison between the size of the decreases in the cable force and the tangential force was also carried out. This was done to assess how a reduction in the size of decreases in the cable force may affect the tangential force. A strong positive correlation was found to exist between the size of the decreases in both normalised cable force and normalised tangential force ($R = 0.79$, $p < 0.05$, Figure 4.5c).

The relationships between negative/positive tangential force and losses/increases in hammer speed were also considered. These relationships were investigated as losses/increases in speed occur when the tangential force is negative/positive in polarity. Considering first the relationship between the force and losses in speed, two correlates were computed to ascertain how these two variables were related. The first was the correlation between the size of speed losses and the magnitude of normalised tangential force at its most negative. A strong negative correlation was found to exist between these two variables ($R = -0.89$, $p < 0.05$, Figure 4.5d). The second correlate computed

was the correlation between the size of speed losses within each turn and the corresponding amount of time that the thrower spent applying negative tangential force. These two variables were not highly related ($R = 0.39$, $p < 0.05$, Figure 4.5e). The effect that the tangential force had on increases in speed was assessed by computing the correlation between increases in hammer speed and the magnitude of normalised tangential force at its most positive within each turn. These two variables were not highly related ($R = 0.44$, $p < 0.05$, Figure 4.5f)

The magnitude of β at its maximum in each turn (tangential force at its most negative) and the corresponding loss in hammer speed were also compared. They were found to have a strong, positive relationship ($R = 0.87$, $p < 0.05$, Figure 4.5g). In addition, the relationship between the magnitude of normalised cable force, when β was at its maximum, and the corresponding loss in hammer speed was investigated. A moderate, positive relationship was found to exist between the two ($R = 0.52$, $p < 0.05$, Figure 4.5h). The relationship between the magnitude of β , at its maximum in each turn, and the increase in speed observed in the subsequent double support was also investigated. These two variables were found to be not highly related ($R = 0.34$, $p < 0.05$, Figure 4.5i).

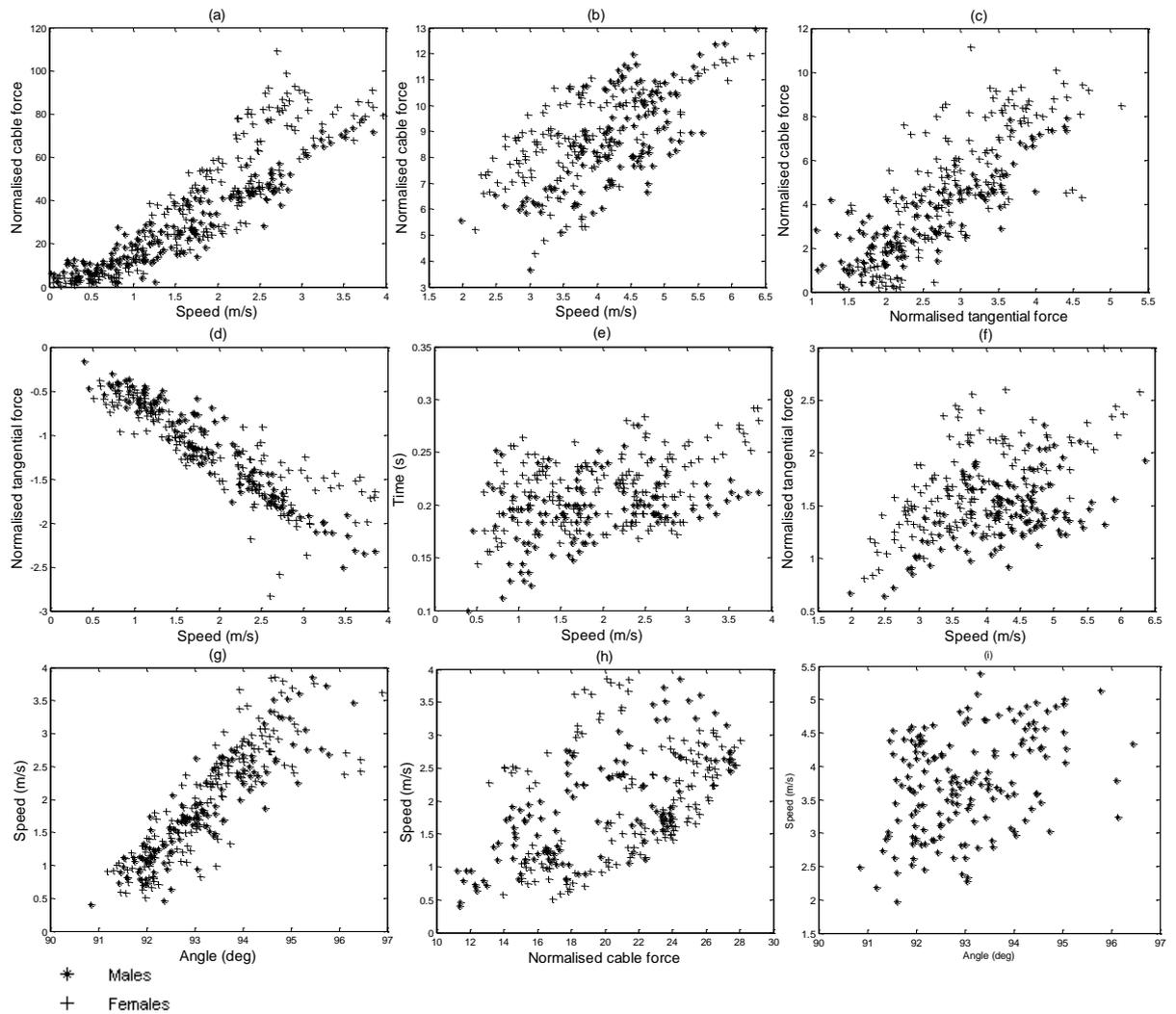


Figure 4.5. Scattergrams of correlate data: (a) decrease in normalised cable force vs. loss in hammer speed, (b) increase in normalised cable force vs. increase in speed (c) decrease in normalised cable force vs decrease in normalised tangential force, (d) normalised tangential force at its most negative vs. loss in hammer speed, (e) time applying negative tangential force vs. loss in hammer speed, (f) normalised tangential force at its most positive vs. increase in speed (g) loss in hammer speed vs. the magnitude of angle β at its maximum in each turn (h) loss in hammer speed vs. normalised cable force, when β is at its maximum in each turn (i) increase in hammer speed in subsequent turn vs. the magnitude of angle β at its maximum in the previous turn.

4.5 Discussion and Implications

The general trends of the traces of hammer speed and cable force (Figures 4.2 and 4.3) are similar to those observed previously in the literature (Bartonietz et al. 1988; Brice et al. 2008; Dapena, 1984; Murofushi et al. 2005) with the males obtaining higher cable force magnitudes than the females. The trends of the traces of the tangential force (Figure 4.4) are similar to that reported by Bartonietz (1994) with the polarity alternating between being positive and negative and there being a single fluctuation occurring within each turn. As has already been discussed, the regions of negative tangential force indicate when the hammer's head is leading the athlete ($\beta > 90^\circ$), and alternately, the regions of positive tangential force indicate when they are pulling in front ($\beta < 90^\circ$).

The tangential force trends observed here differ to the trend reported by Susanka et al. (1987). The data they presented showed that in the final two turns, two fluctuations in the tangential force occurred whereas all subjects in this current study had a single fluctuation. In addition, these fluctuations varied between ± 500 N, which is approximately three times the size of the oscillations in the current study. The data presented by both Susanka et al. (1987) and Bartonietz (1994) are from the same athlete (current world record holder Yuriy Sedykh). The basic shape of the tangential force trace shown by Bartonietz (1994) agrees with that of the current study; however, the magnitude of the peaks is approximately 30% larger than that of the males in this study, reflecting the greater throw distance. The reason for the large differences between the two data sets is unknown. However, the hammer speed data presented by

Susanka et al. (1987) was also questionable. In particular, they observed a loss and increase in hammer speed during the delivery phase which has not been previously reported in the literature which leads to questions relating to the integrity of their data.

The tangential force traces presented here also show secondary oscillations in the positive peak regions. It is thought this may be a reflection of instability in the hammer-thrower system as the athlete attempts to accelerate the hammer. These secondary oscillations are particularly noticeable in the last two turns of the three turn throwers who have less time to accelerate the hammer and are possibly more susceptible to instability.

The mechanical relationship that exists between cable force and hammer speed alone would suggest that larger increases in the magnitude of the cable force will lead to a greater increase in speed. This inference was supported by the high correlation observed here between increases in speed and cable force. These findings suggest that a thrower should aim to apply as large a force as possible during the acceleration phase of each turn. Conversely, the mechanical relationship between the cable force and speed would also suggest that reducing the magnitude of the losses in cable force should lead to a reduction in the corresponding loss in hammer speed. This inference was also supported by the strong correlation observed between losses in speed and cable force. Ideally, there should be no loss in hammer speed and cable force. However, these decreases in speed and force occur during single support when the hammer head is approaching its highest position in the turn. Therefore, it

may be impractical to eliminate them completely due to the reduced stability associated with being in single support. It should also be noted that gravity will also have an effect on the size of speed fluctuations (see section 2.4.2). However, its effect is significantly smaller than that of the cable force (Dapena, 1984).

The strong correlation between hammer speed and cable force also has important implications for the athlete in the training environment. Methods have been reported that allow direct measurement and immediate feedback of cable force magnitude in the training environment (Brice et al. 2008; Hwang and Adrian, 1984; Murofushi et al. 2005). Given the strong correlation that exists between speed and cable force, these types of systems could be used by the athlete and coach to assess how an athlete is developing speed by analysing measured force information. For example, previous studies in the literature have shown that generally each peak in hammer speed and cable force is clearly greater in magnitude than the previous peak (Bartonietz et al. 1988; Brice et al. 2008; Dapena, 1984; Murofushi et al. 2005). If no significant difference was found to exist between the magnitudes of consecutive peaks, then it could be inferred that the thrower has some sort of technique flaw or strength issue that is restricting them from doing so. This type of behaviour was observed here in the traces of one female participant's speed and force data. For this participant, comparison between the peaks in hammer speed and cable force in final two turns of her best throw showed only small increases of 1% and 6% respectively which indicates she is essentially performing an additional turn for little gain in hammer speed. As this behaviour is observed in both the speed and force data,

it is feasible that the athlete and coach could assess this speed development issue by looking at measured force data in the training environment. This would potentially allow the athlete and coach to implement technique changes and assess how these changes are affecting speed development within the training environment. This simple type of assessment shows how simply looking at the trend of hammer speed and cable force can assist with determining performance characteristics of individuals and quickly assessing where an athlete can improve.

While the relationship between cable force and hammer speed is of high importance, the effects other variables have on hammer speed also need to be considered as it may be more effective or simpler to alter them in order to increase hammer speed. The tangential force contributes directly to hammer speed, and for this reason, it is important to have a strong understanding of the relationships between both the cable force and its tangential component, and the tangential force and hammer speed. The strength of the relationship between the size of decreases in both normalised cable force and normalised tangential force observed in this study could suggest that a smaller decrease in cable force may lead to a reduction in the size of the decreases in tangential force. However, it may not be that straightforward. Further investigation needs to be undertaken to determine whether a cause-effect relationship exists.

The periods of negative tangential force coincided with decreasing hammer speed (Figures 4.2 and 4.4), and ideally the athlete should ensure that the effect of these negative periods of tangential force are minimised throughout the

throw. It may not be possible for the thrower to entirely remove the periods of negative tangential force however; reducing the effect these periods have on losses in hammer speed is desirable. There are two ways that it may be feasible for the thrower to minimise the effect of negative tangential force: the first being by reducing the length that these periods occur for and the second by reducing the magnitude of the tangential force itself.

Analysis of the computed correlates indicates that this cohort of throwers, and most probably other throwers of similar ability, could reduce the effect of negative tangential force by reducing its magnitude rather than by reducing the time negative force is applied for. It is unknown whether this would also transfer to throwers who have a higher performance level. However, it must also be considered that reducing its magnitude when negative could have an effect on what occurs when the tangential force returns to being positive in polarity. When the tangential force is positive, the athlete should ensure the force's magnitude is as large as possible. Although, the relationship found here between increases in speed and magnitude of the tangential force when positive suggests that these two variables are not strongly related. In addition, inspection of Figure 4.4 indicates that for most participants the magnitude of the tangential force at its maximum within each turn remains approximately the same irrespective of both turn number (before the final turn) and the magnitude of the preceding minimum in tangential force. This could indicate that for the majority of these athletes the magnitude of the tangential force at its most negative has little effect on the magnitude of the proceeding positive maxima. This is in contrast to the data presented by Bartonietz (1994) for Yuriy Sedykh, who although also showed an

increasingly negative tangential force component, displayed a greater increasing positive component as the throw progressed. This possibly reflects the greater skill level of Yuriy Sedykh compared to the throwers in the current study. Future investigation into this concept needs to occur to determine if it is physically possible for an athlete to reduce the negative tangential component while enhancing the positive component.

Inspection of equation 4.2 indicates that the tangential force magnitude can be altered in two ways: by changing either the magnitude of the cable force or by changing the angle between the hammer velocity and cable force vectors (β). Considering the first of these, if the primary objective of the thrower is to reduce the magnitude of the tangential force when it is negative, then it follows that this can be done by reducing the overall magnitude of the cable force. However, focusing on reducing the magnitude of cable force could be counterproductive to positive tangential force development. This is due to the fact that a reduction to the overall cable force magnitude may lead to additional work being required from the thrower to produce a greater increase in the cable force when it returns to being positive. Additionally, for a reduction in cable force to occur during single support the thrower would be required to increase the magnitude of the radius which could be difficult given that they are already in an unstable position during single support.

As was mentioned above, the second way that a thrower can alter tangential force magnitude is by making changes to the size of the angle between the cable force and velocity vectors (β in equation 4.2). In this study, the magnitude

β at its maximum in each turn (tangential force at its most negative) and the corresponding loss in hammer speed were found to be very strongly related. Theoretically, this means a smaller angle leads to a smaller loss in hammer speed.

One thing to consider is that making changes to the magnitude β at its maximum in each turn could have a detrimental effect on increases in speed in the subsequent double support phase. With this in mind, the relationship between β , at its maximum in each turn, and the subsequent increase in hammer speed was also determined here. A weak relationship was observed between these two variables and this could suggest that, for this cohort of throwers, altering β at its maximum in each turn may have little effect on what happens in the subsequent double support phase, when the speed of the hammer is being increased by the hammer thrower.

The relationship between the magnitude of normalised cable force at the point in time when β is at its maximum within each turn and the corresponding loss in hammer speed was also investigated. A moderate relationship was found to exist between these two variables. These findings suggest that β has a greater effect on losses in hammer speed than the actual magnitude of the cable force. This, in turn, could imply that it is more beneficial for athletes to make changes to technique that reduce β rather than cable force magnitude during single support.

4.6 Conclusion

Analyses of the traces of tangential force showed that decreases in hammer speed occur when the tangential force was negative and similarly, increases occurred when it was positive. The correlation analyses carried out in this study suggest that the most effective way to minimise the impact of negative tangential force is to reduce angle by which the cable force lags behind the radius of rotation (β) as opposed to reducing the amount of time spent applying negative tangential force. Further investigation into how an athlete would do this and whether this is a feasible option given the range of variation of the angle needs be carried out by investigating the kinematics and kinetics of the thrower.

Future focus now needs to address the hammer throw technique to identify aspects of an athlete's kinematics that affect the hammer speed and the angle between the cable force vector and the instantaneous direction of the radius of rotation. This is investigated in Chapter 5 of this thesis.

4.7 Chapter Summary

- Purpose of this study was to investigate the relationship between cable force and linear hammer speed and to identify how the magnitude and direction of the cable force effects the fluctuations in linear hammer speed.
- The hammer's linear velocity and the cable force and its tangential component were calculated via hammer head positional data.

- Strong correlation was observed between decreases in linear hammer speed and:
 - Decreases in the cable force.
 - The lag angle at its maximum (when tangential force is at its most negative).

- The findings presented here indicate the most effective way to minimise the effect of the negative tangential force is to reduce the size of the lag angle

Chapter 5 – An analysis of the thorax-pelvis separation angle and its effect on hammer kinetics and kinematics in the hammer throw.

5.1 Chapter Statement

The study presented in the previous chapter of this thesis investigated the relationship between cable force and hammer speed. This study largely focused on the relationship between the tangential component of the cable force and losses in speed. While this study gave good insight into the relationship between these variables, it did not investigate the relationship between them and thrower kinematics. The study presented in this present chapter continues on from the previous work and investigates the relationship between the aforementioned hammer kinetic and kinematic variables and pertinent thrower kinematic variables.

The information and findings reported in this chapter are adapted from the following journal article that is currently under review:

Brice, S. M., Ness, K. F., Evringham, Y. L., & Rosemond, D. An analysis of the thorax-pelvis separation angle and its effect on hammer kinetics and kinematics in the hammer throw. Under review.

5.2 Introduction

Throughout the hammer throw the speed of the hammer fluctuates primarily as a result of the tangential component of the cable force (tangential force) fluctuating between being positive and negative (Dapena, 1984). Tangential force was discussed in detail in Chapter 4, and it was found that the periods of negative force occur during the early stages of single support. Much of the past literature suggests that the hammer can only be accelerated in the double support phase (Bartonietz, 2000; Bartonietz, Barclay and Gathercole, 1997) as it is not possible for the thrower to actively influence the velocity in the single support phase (Rojas-Ruiz & Gutierrez-Davila, 2009). However, it has been suggested that throwers could in fact increase the speed of the hammer during the single support phase by increasing the vertical velocity of the hammer (Maheras, 2009). The majority of literature focuses on how throwers can actively increase the speed of the hammer within each turn, specifically during the double support phase with little focus being put towards how throwers could reduce the size of losses in speed in the subsequent single support phase. Ideally, the losses in hammer speed that occur in the single support phase should be minimised (Morley, 2003a).

In Chapter 4, the relationship between the tangential force and speed losses was investigated in detail. It was found that the magnitude of the tangential force at its most negative, rather than the amount of time spent applying negative force, had the greatest effect on losses in speed. Given this, it was

hypothesized that throwers may be able to reduce the size of losses in speed if they can reduce the magnitude of the tangential force when it is negative.

The terms in equation (4.2) indicate that a thrower can reduce the magnitude of the tangential force in two ways: by reducing the magnitude of the cable force or by reducing the angle between the force and velocity vectors (β in equation 4.2). The findings presented in Chapter 4 suggest that a thrower is best able to reduce the size of losses in speed, caused by the tangential force being negative, by reducing the magnitude of β as opposed to reducing the magnitude of the cable force.

Hammer throw technique is strongly influenced by movement of the trunk (Otto, 1991; Morley, 2003a). It is widely accepted that the angle between the shoulders and pelvis (shoulder-pelvis separation angle) increases during single support and decreases during double support as the thrower accelerates the hammer (Morriss & Bartlett, 1995a, 1995b; Otto, 1991). While movement of the trunk or shoulders relative to the pelvis has been discussed in coaching literature, it has received little research attention (Judge, Hunter & Gilreath, 2008). The magnitude of the thorax-pelvis separation angle has, however, been investigated in a number of other sports that utilise thorax rotations such as discus and golf.

Like the hammer throw, the speed of the discus at release is the most important determinant of range (Bartlett, 1992), and the relationship between discus velocity and thorax-pelvis separation has been investigated in a number of studies (Leigh et al. 2008; Leigh & Yu, 2007;). Leigh et al. (2008) analysed the techniques of 51 male and 53 female skilled discus throwers and found that throwers should maintain their hip-shoulder and shoulder-arm separation angles during the throw as this allows the discus to travel over a longer path and results in the horizontal component of the release velocity being larger.

In golf studies, the thorax-pelvis separation angle is referred to as the X-factor and is typically determined by computing the difference between the thorax and pelvis axial rotation angles projected onto the horizontal plane (Chu, Sell & Lephart, 2010; Horan et al. 2010; Myers et al. 2008). The relationship between X-factor and golf performance has been researched extensively. A number of studies have reported positive relationships between X-factor and clubhead velocity which indicates that athletes could increase ball velocity by increasing the X-factor during the golf swing (Chu, Sell & Lephart, 2010; Myers et al. 2008). More recent work has tested the validity of methods used to calculate the X-factor, and there was no mechanically meaningful relationship found to exist between X-factor and the maximum clubhead velocity (Kwon et al. 2013).

The purpose of the study presented in this chapter was to investigate thorax-pelvis separation in the hammer throw and its relationship with key hammer kinetic and kinematic variables. In this present study, the relationship between thorax-pelvis separation angle and the following variables was investigated:

- size of losses in speed
- magnitude of the tangential force at its most negative
- maximum size of the angle between the cable force and velocity vectors (β in equation 4.2) when the tangential force is negative.

It was hoped the findings of this investigative study would give athletes and coaches a clear indication as to how to reduce the size of losses in the hammer speed, by making changes to the magnitude of the thorax-pelvis separation angle at key times in the throw.

5.3 Methods

Five male and five female hammer throwers (described in section 3.3 of this thesis) participated in this study. Participants were asked to complete ten throws with a competition standard hammer (7.26 kg for males and 4 kg for females) that had retro-reflective markers positioned on the hammer's cable at known distances from the centre of the hammer's head. In addition, retro-reflective markers (15 mm in diameter) were positioned on the anatomical landmarks described in Table 3.2 which is in accordance with the Vicon Plug-in Gait marker placement protocol (Davis III et al. 1991).

A 21 infra-red camera system sampling at a frame rate of 250 Hz was used to record all three-dimensional marker coordinate data. The recorded video footage was post processed in Vicon Nexus using the same data processing and filtering protocols outlined in section 3.5.1. The hammer marker positional data were used along with direction cosines to determine the hammer head three-dimensional positional data (see section 3.5.3 for equation details). These hammer head positional data were then used to determine linear hammer speed and the cable force and its tangential component (see section 4.3 for equations). All force data were normalised for hammer weight to account for the difference between the hammers used by the two genders.

The filtered body marker data were used to create rigid models of the thorax and pelvis via the Plug-in Gait modelling functions in Vicon Nexus. The markers that were used to model the thorax were positioned on the sterno-clavicular notch, xiphoid process, spinous process of the C7 vertebra and the spinous process of the T10 vertebra. The markers that were used to model the pelvis were positioned on the left and right anterior superior iliac spine and the left and right posterior superior iliac spine. The angle between the sagittal axes (or frontal planes) of the thorax and pelvis segments (thorax-pelvis separation angle) was output from Vicon Nexus. In this study, thorax-pelvis separation angle was positive when the thorax leads the pelvis and negative when the pelvis leads the thorax (Figure 5.1). Traces of the thorax-pelvis separation angle were produced to build an understanding of how a thrower moves their thorax relative to their pelvis as these data have not been specifically reported in the literature.

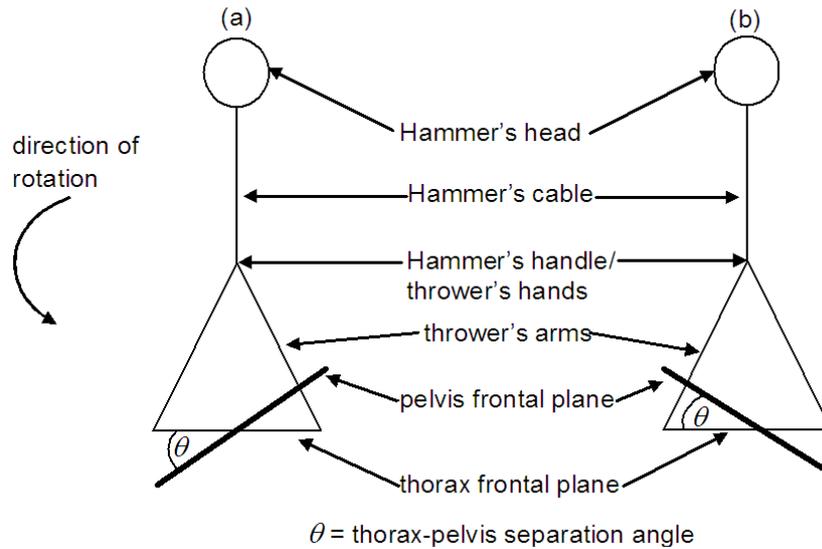


Figure 5.1. Overhead view of the thorax-pelvis separation angle. Angle is defined as being (a) negative (pelvis leading thorax) and (b) positive (thorax leading pelvis) for a right-handed thrower.

For each turn, the loss in speed, tangential force at its most negative and the angle between the linear velocity and cable force vectors at its greatest (maximum lag angle, β in equation 4.2) were determined. These values were averaged over the ten throws so that each participant had a mean value of the above mentioned variables for each turn. The thorax-pelvis separation angle at its smallest within each turn was also determined.

Simple linear regression models were used to examine the relationships between the separation angle at its smallest, and the above mentioned hammer kinetic and kinematic variables. The separation angle at its smallest was set as the dependent variable for each regression that was computed. Pearson's correlation and the associated p-values (p) measured the strength of these relationships. A relationship was deemed to be significant if $p < 0.05$. All correlations were classified using the definitions described by Hopkins (2006).

Scatterplots of the bivariate relationships between each of the correlates were also explored for the effects of outlying observations, and a cluster analysis was also performed in IBM SPSS statistics (IBM Corporation, New York US) to confirm the existence of any outliers. Post hoc power analyses were also performed in G*Power (Erdfelder, Faul & Buchner, 1992). This was done to assess the statistical power of the correlates. Power was deemed to be adequate if it was greater than 80% (Cohen, 1988).

Three different turning methods were utilised by the participants of this study: three turn (n = 2), four turn (n = 7) and five turn (n = 1). For each of the correlation analyses the turns were classified as turn one, turn two, second last turn and final turn. Table 5.1 shows which turn number of the three different turning methods was included in each of the four aforementioned analysis classifications. For three turn throwers, turn two data were used in both the second turn and second last turn correlation analyses, whilst the turn three data for the five turn thrower was not included in any of the correlation analyses.

Table 5.1: Turn number used in each of the correlation analyses of this study.

No. of turns	First turn analyses	2 nd turn analyses	2 nd last turn analyses	Final turn analyses
3	1	2	2	3
4	1	2	3	4
5	1	2	4	5

5.4 Results

The thorax-pelvis separation angle was found to be predominantly negative throughout each throw (data for each participant's furthest throw are displayed in Figures 5.2 and 5.3). For the majority of participants, the size of the separation angle decreased during double support and increased during single support (Figures 5.2, 5.3a and 5.3b). Exceptions to this were three female participants whose data are displayed in Figures 5.3c, 5.3d and 5.3e. For all three of these females, turn one data indicated that the angle behaved as it did for the other seven participants. For two of these females, this trend was also observed in turn two (Figures 5.3c and 5.3e).

The behaviour of the separation angle for the remaining turns of the three aforementioned females differed somewhat, particularly during the single support phases. For one of these females (Figure 5.3c), the size of the angle during turns three and four began to increase later in the single support phase when compared to the other participants, while for another (Figure 5.3e) the magnitude of the angle had periods where it both increased and decreased during the single support phases of turns three, four and five. For the remaining female participant, whose data are displayed in Figure 5.3d, the angle magnitude was found to increase and decrease during both support phases for turns two, three and four.

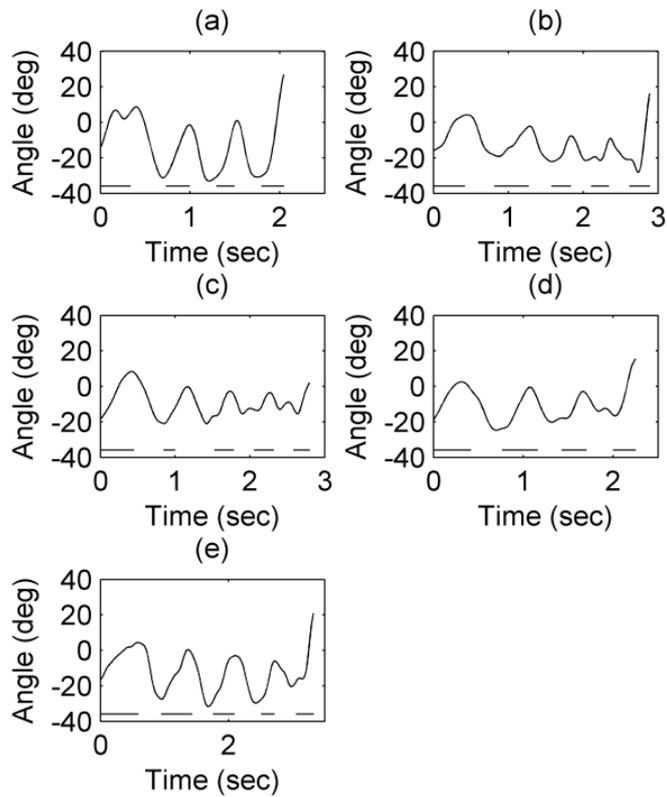


Figure 5.2. Thorax-pelvis separation angle for the furthest throw of the male participants: (a) three turn thrower (63.22 m), (b) four turn thrower (61.45 m), (c) four turn thrower (60.71 m), (d) three turn thrower (57.69 m) and (e) four turn thrower (42.61 m). Note: black lines at the bottom of each graph indicate when the athlete was in double support.

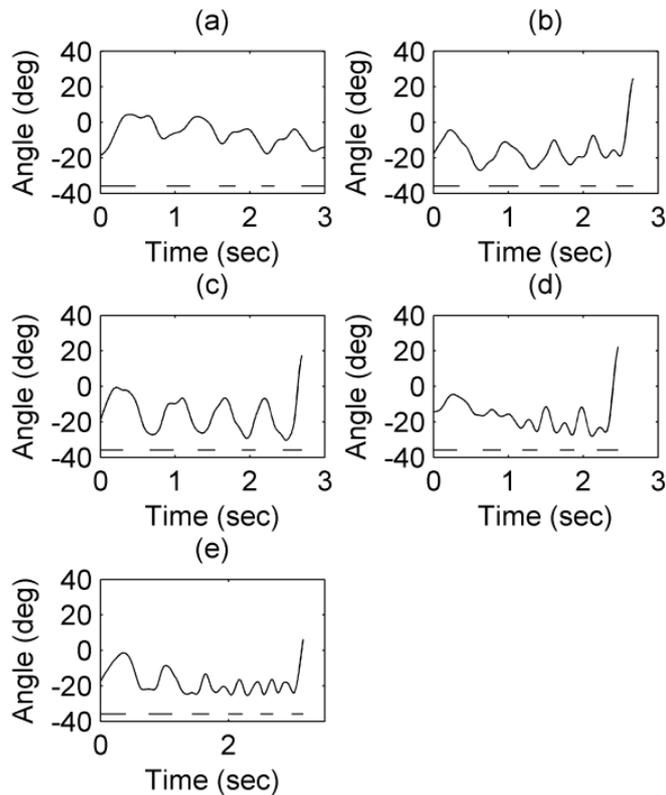


Figure 5.3. Traces of the thorax-pelvis separation angle for the furthest throw of female participants: (a) four turn thrower (59.86 m), (b) four turn thrower (57.59 m), (c) four turn thrower (55.66 m), (d) four turn thrower (54.54 m) and (e) five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete was in double support.

Strong, positive correlations were found between normalised tangential force at its most negative (F_{\min} in Table 5.2), and the separation angle at its smallest in turn two ($R = 0.79$, $p < 0.05$, power = 0.92) and the second last turn ($R = 0.71$, $p < 0.05$, power = 0.81). No other correlates were found to be statistically significant. However, scatterplots displaying these bivariate relationships revealed that three participants produced consistently larger minimum separation angles than the other seven participants (indicated by the triangle markers in Figures 5.4, 5.5 and 5.6). Furthermore, these data points

corresponded to the three lightest participants, who all happened to be female. These three points formed a cluster of their own following a hierarchical cluster analysis based on a squared Euclidean distance measure (Johnson & Wichern, 2007). Hence, the correlation measures were recomputed with these three points removed (Table 5.2). The strength of the relationship between the minimum separation angle and the tangential force at its most negative subsequently increased (Table 5.2). Moreover, this relationship was also observed for turn one. While the turn one result is statistically significant, this was caused by an additional outlier affecting the correlation calculation (indicated by the circle in Figures 5.4, 5.5 and 5.6). Evidence generated from a cluster analysis supported this point to be distinctively different from the rest when it was found to be grouped in the same cluster as the other three outliers for turn one. When this additional data point was omitted from the correlation calculation, the relationship was no longer statistically significant for turn one (Table 5.2).

A number of other strong, statistically significant relationships were found to exist when the three outliers were omitted from the correlate calculations in Table 5.2. A very strong, negative relationship was found between minimum separation angle and the subsequent loss in speed during the single support phase for turn one, turn two and the second last turn. There was also a strong, negative relationship between minimum separation angle and the maximum lag angle between the cable force and linear velocity vectors. These relationships were significant for turn one, turn two and the second last turn. However, as was with the previous result for the tangential force, the first turn result was

affected by an additional outlier (indicated by the circle marker in Figures 5.4, 5.5 and 5.6).

A number of other strong, statistically significant relationships were found to exist when the three outliers were omitted from the correlate calculations in Table 5.2. A very strong, negative relationship was found between minimum separation angle and the subsequent loss in speed during the single support phase for turn one, turn two and the second last turn. There was also a strong, negative relationship between minimum separation angle and the maximum lag angle between the cable force and linear velocity vectors. These relationships were significant for turn one, turn two and the second last turn. However, as was with the previous result for the tangential force, the first turn result was affected by an additional outlier (indicated by the circle marker in Figures 5.4, 5.5 and 5.6).

The power values obtained from the power analyses (Table 5.2) revealed that the statistical power (post hoc) was above 80% for most of the statistically significant correlates. It should be noted that the statistical power for the statistically significant relationships for second last turn between minimum separation angle and speed loss, and minimum separation angle and the tangential force at its most negative were below 80% (69% and 62%, respectively).

Table 5.2: Persons correlation coefficients for relationship between thorax-pelvis separation angle at its smallest within each turn and selected hammer kinetic and kinematic variables.

Variable	Turn one ^b			Turn two ^a			2 nd last turn ^a			Last turn ^a					
	R	p	power	R	p	power	R	p	power	R	p	power			
F _{min}	0.19#	0.72	0.06	0.86	0.01	0.81	0.95*	0.00	0.97	0.78*	0.04	0.62	0.48	0.27	0.19
Speed loss	0.22#	0.67	0.07	-0.77*	0.04	0.60	-0.97*	0.00	0.99	-0.81*	0.03	0.69	-0.51	0.20	0.22
β at maximum	-0.49#	0.32	0.16	-0.90	0.01	0.89	-0.88*	0.01	0.85	-0.87*	0.01	0.83	-0.71	0.08	0.48

Asterisks indicate statistical significance ($p < 0.05$); ^aThree females excluded from all these analyses; ^bRecomputed with an additional outlier excluded (Indicated by the circle marker in Figures 3(a), 4(a) and 5(a)).

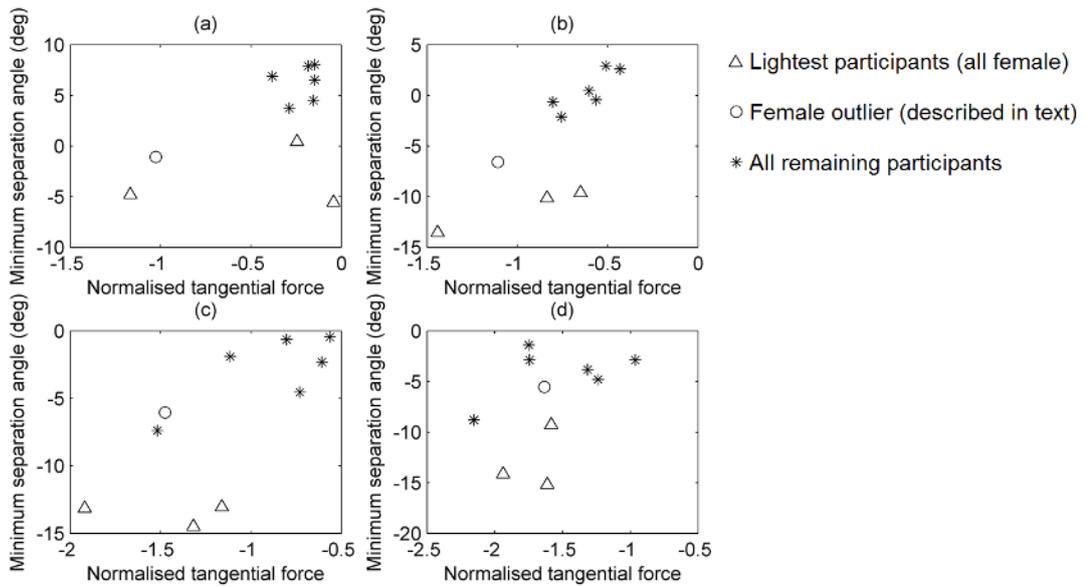


Figure 5.4. Scatterplots of data used to obtain correlations between minimum separation angle and normalised tangential force at its minimum (F_{\min} in Table 5.2) in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

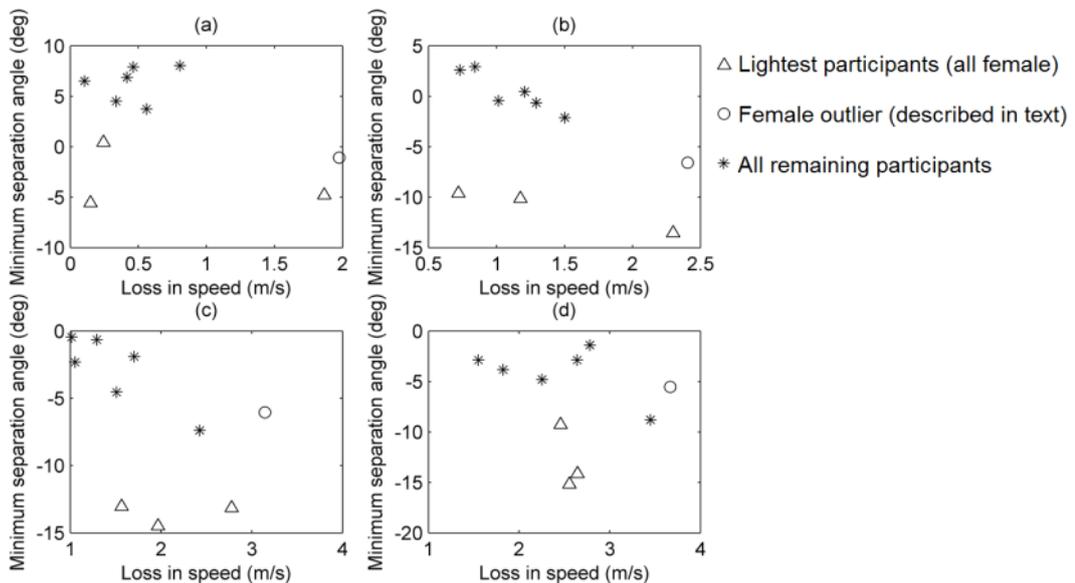


Figure 5.5. Scatterplots of data used to obtain correlations between minimum separation angle and the subsequent loss in speed in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

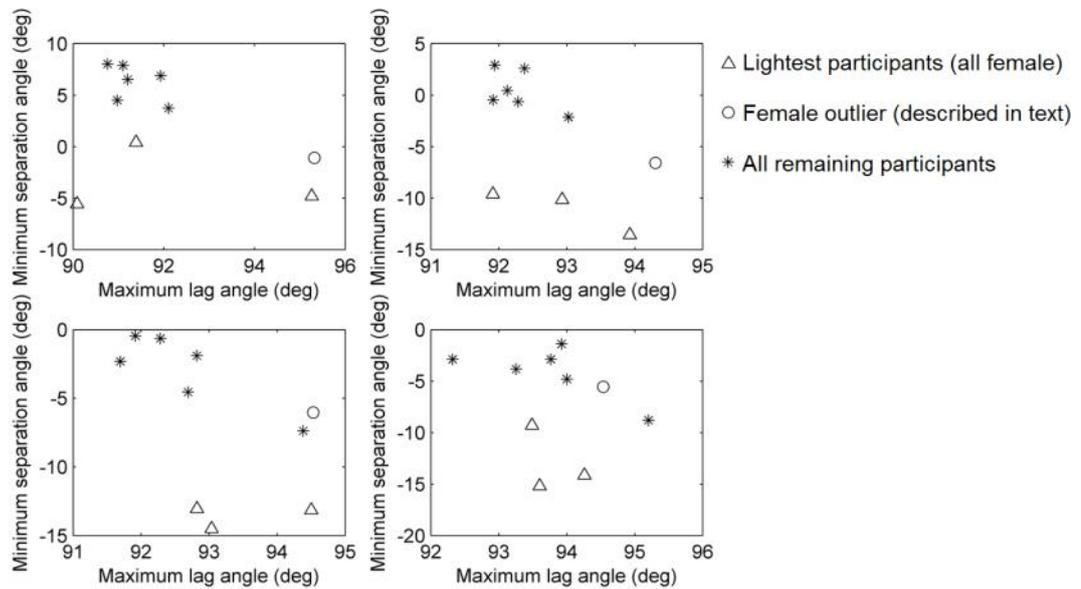


Figure 5.6. Scatterplots of data used to obtain correlations between minimum separation angle and β at its maximum in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

5.5 Discussion and Implications

The purpose of this study was to investigate the thorax-pelvis separation in the hammer throw. The trends of the traces of thorax-pelvis separation angle in Figures 5.2 and 5.3 show that the angle is predominantly negative which indicates that the pelvis is typically leading the thorax throughout the throw. The magnitude of this angle was also found to generally increase during single support (when hammer speed is decreased) and decrease during double support (when hammer speed is increased) which is consistent with what has been reported previously in the literature (Morriss & Bartlett, 1995a, 1995b;

Otto, 1991). These traces also give an indication as to the size of the separation throughout the throw which has not been reported previously in the literature.

For the participants whose data are displayed in figures 5.3d and 5.3e, there are small oscillations present in the trough regions (e.g. between 1 and 1.5 seconds for the female subject in Figure 5.3d). It is unknown why these oscillations occur but, these two participants were the least skilled females of this cohort (best throws of 54.54 m and 54.43 m respectively). These two participants were also two of the three outliers excluded from the correlate calculations for the data reported in Table 5.2. This could indicate some technique flaw or strength issue resulting in these participants not being in complete control of the hammer.

The strength of the relationships reported in Table 5.2 indicate that hammer speed losses during single support are smaller when the thrower is able to reduce the angle between the frontal planes of the thorax and pelvis during the preceding double support phase, particularly in the second and second last turns of the throw. This is in agreement with coaching literature that suggests that the thorax-pelvis separation should be approximately zero when the hammer is at its lowest point (Morley, 2003a).

While it is accepted that the losses in speed that occur during single support can't be eliminated, throwers should ensure that the magnitude of these losses are kept to a minimum (Morley, 2003a) as once they return to double support they first need to account for these losses before they can continue to build the

hammer's linear speed. This leads to the suggestion that throwers of this cohort, and those of similar ability, should aim to reduce the thorax-pelvis separation angle by as much as possible during the double support phase by focusing on rotating the thorax in the direction of the throw. This would be rotation in the anticlockwise direction for a right-handed (Figure 5.2) thrower and clockwise for a left-handed thrower. Currently, it is unknown if it is possible for a thrower to manipulate the thorax-pelvis separation during the throw. However, the period of double support is when the athlete is at their most stable and Figures 5.2 and 5.3 indicate that generally the angle is already being decreased by the participants during double support so it is most probably the period of time when it is easiest for an athlete to manipulate the separation angle.

Reducing the thorax-pelvis separation during double support also appears to result in the maximum lag angle between the cable force and velocity vectors (β) being smaller and a smaller magnitude for the normalised tangential force at its most negative in the subsequent single support phase (Table 5.2). In Chapter 4, it was found that this lag angle at its greatest has the greatest influence on the size of losses in speed within each turn. Hence, any reduction in the size of this lag angle will likely lead to smaller losses in linear hammer speed.

One limitation of this study that needs to be considered is the utilisation of the Pearson's correlation coefficient as extreme cases (outliers) can result in correlates that are misleading (Asuero, Sayago & González, 2006). In this

present study, scatterplots were produced and cluster analyses were performed to determine the existence of outliers in the data sets. Where outliers were found to exist, the correlates were recomputed with outliers removed. Another limitation of Pearsons correlation is it assumes the relationship between the two variables is linear. The exploratory data analyses that were performed in this study suggested this assumption was reasonably met. Another assumption of the correlation analysis is that which deals with homoscedasticity; where the variability for one variable is similar to the variability of the other variable. The initial investigations, where all subject's data were included, violated this assumption and hence these results should be interpreted with care. This issue was resolved by working with a more homogenous subset of data that excluded participants from the more variable cluster.

Another limitation of this study is the throwing ability of the participants. The current world record distances in the hammer throw are 86.74 m and 79.42 m for men and women respectively (IAAF, 2013). In this study, the average distance thrown was 54.3 ± 7.6 m for the male participants and 53.9 ± 3.2 m for the female participants which are considerably lower than the distances thrown by the world's leading athletes. Therefore, any of the findings found of this study can only be applied to this cohort or throwers of similar ability. Further investigation needs to be carried out to ascertain whether the relationships observed here hold true for more skilled throwers.

5.6 Conclusion

The relationship between thorax-pelvis separation angle and key kinematic and kinetic variables of the hammer were analysed in this study. Thorax-pelvis separation angle was chosen for analysis as it was thought that with training an athlete could manipulate this variable, particularly during double support. The results of this study indicate that this cohort of throwers (and throwers of similar ability) should aim to reduce the thorax-pelvis separation angle during double support by as much as possible, specifically during turn two and the second last turn. This results in a smaller loss in speed during the subsequent single support phase.

Future work should be done to assess if the relationships observed here are present for more highly skilled hammer throwers. In addition to this, an intervention study should be undertaken to assess if an athlete can adjust their technique by making the changes outlined here and assess how such changes may lead to enhanced performance.

5.7 Chapter Summary

- The study detailed in this chapter investigated the relationship between thorax-pelvis separation angle and key hammer kinetic and kinematic variables.

- Thorax-pelvis separation was found to increase during single support and decrease during double support.
- Losses in speed were found to be smaller when the separation angle was decreased in the preceding double support phase, specifically in turn two and the second last turn.

The findings outlined in this chapter indicate that throwers can reduce the size of losses in speed by reducing the size of the thorax-pelvis separation during double support.

Chapter 6 – Validation of a method to determine hammer speed from cable force in the training environment.

6.1 Chapter statement

In Chapters 4 and 5 of this body of work two studies were presented that investigated speed development in the hammer throw and how an athlete could alter their technique to potentially enhance this. This chapter presents the findings of a validation study that was aimed at finding a method that would allow the athlete and coach to assess speed development in the training environment. It was hoped this type of device would allow the athlete and coach to implement the proposed technique changes outlined in Chapter 5 and assess how these technique changes effected speed development.

The information and findings reported in this chapter are adapted from the following journal article:

Brice, S. M., Ness, K. F., & Rosemond, D. Validation of a method to determine hammer speed from cable force in the training environment. *Journal of Sport and Health Sciences*, In press.

Published version of this article is included in Appendix D.

6.2 Introduction

In Chapter 4 of this thesis, speed fluctuations in the hammer throw were investigated and a strong relationship ($R = 0.87$, $p < 0.0001$) was observed between the size of these fluctuations and the maximum angle (β in equation 4.2) between the cable force and linear velocity in each turn. These findings suggest that during single support, a thrower could reduce the size of speed losses if they decrease the size of this angle. By reducing the size of the losses in speed, the overall speed development will be enhanced which is crucial to throw success given the relationship that exists between release speed of the hammer and throw performance. It was reported in Chapter 4 that the variation in β is not large. As such, it may be difficult for an athlete and/or coach to assess how technique alterations are affecting this angle. The only accurate way to assess whether an athlete is reducing the maximum size of β is to directly measure the angle. It may also be possible to assess whether an athlete is reducing this angle by monitoring the associated losses in hammer speed, given the relationship that exists between these two variables.

Currently, β and linear speed can only be accurately determined from hammer head positional data. Automatic tracking is the quickest method that could be used to collect this positional data. However, this is time consuming, post-processing is required and immediate feedback in the training environment is not possible via this method. For an athlete to be able to improve technique, it is vital to have accurate information about their performance, and any delay in providing the information reduces the likelihood that the athlete will be able to

make effective use of the feedback (Sanderson, McClements & Gander, 1991). Therefore, it would be highly beneficial if there were a method that allowed accurate feedback in the training environment on the behaviour of the linear hammer speed. This would allow an athlete and coach to ascertain if technique alterations are beneficial or detrimental.

It is also possible to attain accurate linear hammer speed data via utilisation of its relationship with the instantaneous radius of curvature and the centripetal force. The relationship that exists between centripetal force (F), linear velocity (v) and instantaneous radius of curvature (r) is given by,

$$F = \frac{mv^2}{r} \quad (6.1)$$

where m is the mass of the hammer. The mass term in the above equation is the only constant. Therefore, in order to attain accurate linear speed data via the above equation, both the centripetal force and radius of curvature would need to be directly measured throughout the throw.

Murofushi et al. (2005) presented a method that uses the above relationship along with the relationship between linear and angular velocity to determine linear hammer speed and radius of curvature during the throw. This measuring system added a total mass of 0.37 kg to the hammer and consisted of two strain gauges, that measured the cable force (not centripetal force), and two single axis accelerometers that were used to determine the angular velocity. There was good agreement between the measured linear speed and the speed calculated from hammer head positional data. However, there was an obvious phase lag between the two data sets. It was hoped that in this current study a

more accurate method could be developed to determine hammer speed that would eliminate the phase lag observed in the data set of Murofushi et al. (2005). In addition, it was hoped that a measuring device that added negligible mass to the hammer system could also be utilised.

Brice et al. (2008) reported an alternate method to directly measure cable force magnitude in the training environment. This system added negligible mass to the hammer system and consisted of a single strain gauge mounted directly on the hammer's cable. An average error 3.8% for a force of 2000 N when compared with cable force derived from hammer head positional data was reported. It is important to note that the cable force itself is not equal to the centripetal force. The cable force consists of three components; normal, radial, and tangential to the instantaneous circle of rotation (Dapena, 1984; Tutevich, 1969). The radial component is considerably larger than the other two components, and it is nearly equal to the centripetal force acting on the hammer. Due the complex motion of the hammer during the turns, it is not possible to derive a simple, usable expression relating the hammer speed to the cable force. However, since the cable force is by far the largest contributor to the centripetal force in equation (6.1), it was thought that the measurement system described above could be used in conjunction with a regression model to predict speed squared from cable force.

The purpose of this study was to investigate whether the relationship between the cable force and squared linear hammer speed could be used to develop a model that would allow speed to be predicted from measured cable force in the

training environment. This type of information could be utilised by the athlete and coach to assess if changes in technique are reducing or increasing the losses in speed that occur within each turn.

6.3 Methods

Five male and five female hammer throwers (described in section 3.3 of this thesis) participated in the study detailed in this chapter. Participants were required to perform ten throws with hammers instrumented with a strain gauge device (sampling at 500 Hz), previously described by Brice et al. (2008). This device measured the cable force throughout each throw (measured force) and was calibrated prior to data collection (see section 3.4.2 of this thesis for calibration procedures). Retro-reflective markers were positioned on the hammer's cable at known distances from the centre of the hammer's head. A 21 infra-red camera system sampling at a frame rate of 250 Hz was used to collect the marker three-dimensional coordinate data. All marker positional data were post-processed using the procedures outlined in section 3.5.1 of this thesis. These marker data and direction cosines were then used to determine the three-dimensional coordinate data for the centre of the hammer's head (see section 3.5.3) from which linear hammer velocity (calculated speed) and cable force (calculated force) were calculated. All calculated and measured force data were normalised for hammer weight to account for the fact that males use a heavier hammer than females.

Two regression models were developed that allowed speed to be predicted from measured force data (predicted speed). The calculated speed data and calculated force data were used to develop these regression models. All calculated speed data used in the regression model development were squared due the mechanical relationship that exists between centripetal force and linear velocity squared (equation (6.1)).

The first regression model was derived from the square of the calculated speed and the calculated force (non-shifted regression). While the second model was derived from the square of the calculated speed and a time-shifted calculated force (shifted regression). The shifted regression model was developed because the work outlined in Chapter 4 showed a phase lag between speed and cable force. It was thought that accounting for the phase lag in the model development may lead to a model that would produce speed data that were more accurate.

As the magnitude of this phase lag between the speed and cable force varies depending on turn number, throw and athlete it is not possible to apply the same time-shift to every throw. It was therefore decided to time-shift the calculated force such that for each throw the final peaks in the calculated force and calculated speed coincided. This time-shift was applied to ascertain if removal of the phase lag resulted in a more accurate regression. As only the final peaks were aligned, there was no change in the frequency of the force data.

The calculated speed and calculated force data used to calculate the shifted regression were also trimmed as the final peak in the calculated force data occurred prior to release whereas the final peak in speed occurred at release. The calculated force data were trimmed so that the final peak was the final data point and the calculated speed data were trimmed by the same amount at the start so that both data sets were the same size.

A shifted and non-shifted regression equation was developed for each of the participant's ten throws. All data points of each throw were used to develop these equations. The Matlab software suite was used to determine the regression equations. The y-intercepts for both the shifted and non-shifted equations were forced through (0,0) since equation (6.1) predicts zero speed for zero cable force. Averages of the gradients of the two linear regression equations were determined for the cohort.

The shifted and non-shifted regression models were then used to predict speed squared from measured force data. The square root of these squared speed data was then taken to determine linear hammer speed (predicted speed). It was expected that the predicted speed data would closely agree with the magnitude of calculated speed for each trial. However, it was expected that the phase lag that exists between cable force and linear hammer velocity, previously described above, would still be evident in the predicted speed data. This would result in peaks in the predicted speeds not coinciding with those in the calculated speeds.

To reduce the effect of the phase lag between the measured force and calculated speed, all measured force data were also time-shifted and trimmed so that the final peak in the measured force coincided with release. As with the calculated force, the magnitude of the phase lag varies depending on turn number, throw and athlete so it is not possible to apply the same time-shift to every throw. It was hoped that using time-shifted measured force data would result in predicted speed data that were more closely matched to both the magnitude and waveform of the calculated speeds than if the time-shift were not applied.

The predicted speed data were then compared with the calculated speed data to ascertain the level of accuracy. The root mean square of the differences (RMS) was determined to compare the closeness in magnitude between the predicted and calculated speeds for each throw of each participant (Mayagoitia, Nene & Veltink, 2002). These RMS values were then used to determine the average RMS values for the entire group. The average RMS difference between the calculated and predicted release speeds was also determined.

The coefficient of multiple correlation (CMC) was determined to assess the closeness in the shapes between the predicted and calculated speed waveforms for each throw of each participant (Kadaba et al. 1989; Mayagoitia et al. 2002). The average CMC values was then determined for the entire group. A schematic of the process outlined here is shown in Figure 6.1.

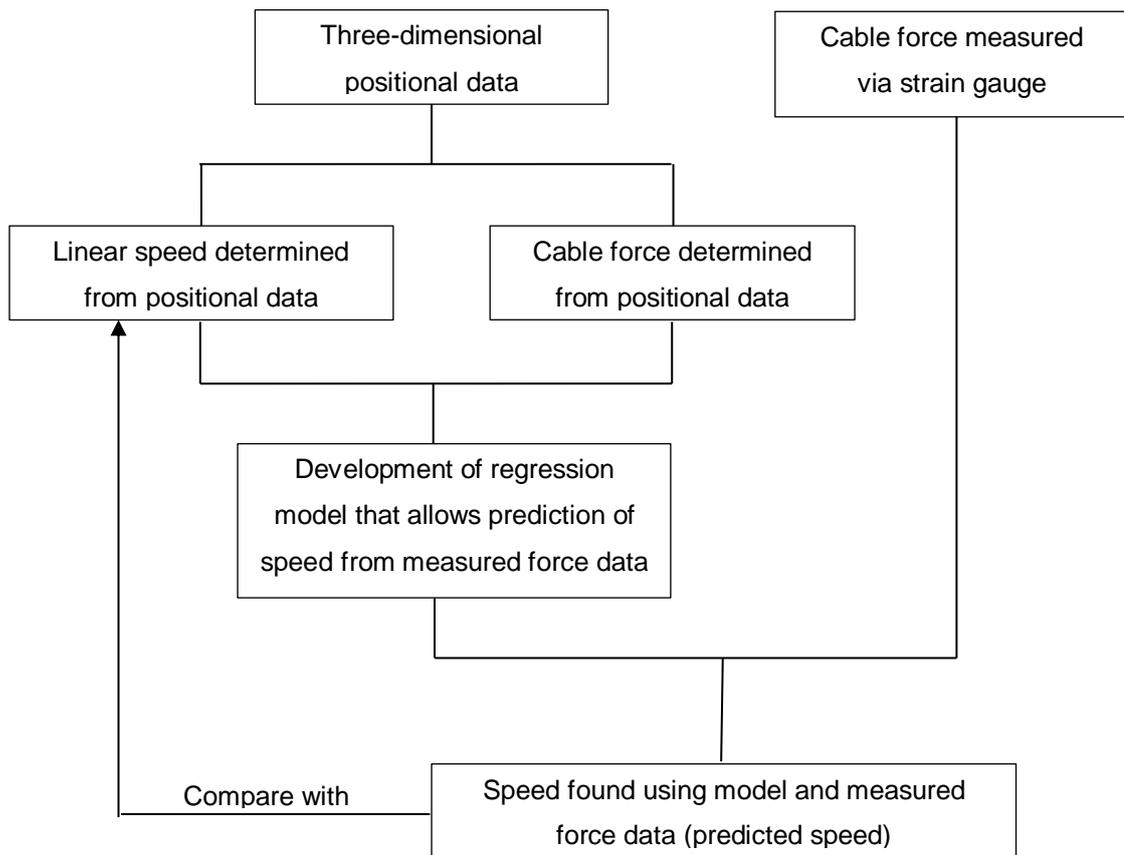


Figure 6.1. Schematic of the data processing undertaken to validate the predicted speed data.

6.4 Results

The regression equations, CMC values and RMS values of the two models are similar (Table 6.1). Both models give high CMC values (0.96 and 0.97). In addition, the reported RMS values of 1.27 m/s and 1.05 m/s are relatively low for the non-shifted and shifted models respectively. The average percentage difference between the calculated speeds and the speeds determined via the non-shifted and shifted models were 6.6% and 4.7% respectively.

For the release speed, the RMS differences between the calculated and predicted values are 0.69 ± 0.49 m/s and 0.46 ± 0.34 m/s for the non-shifted and shifted models respectively.

Table 6.1. Regression equations used to predict speed squared from normalised measured force data, the coefficient of multiple correlation (CMC) and the root mean square (RMS) of the difference between the calculated speed and the predicted speed. The numbers in the table show the means and associated standard deviations of the individual throws. Standard deviations indicated in brackets.

	Gradient	y intercept	CMC	RMS (m/s)
Non-shifted	16.35 (0.48)	0	0.96 (0.05)	1.27 (0.65)
Shifted	17.08 (0.59)	0	0.97 (0.04)	1.05 (0.59)

6.5 Discussion and Implications

The magnitudes of the predicted speeds found using the two regression models were similar to the magnitudes of the calculated speeds as the RMS values were both low (Table 6.1). The shifted model gives both lower overall RMS difference in speeds and in particular lower RMS difference in release speed. The waveforms of the predicted speeds were also similar to the waveforms of the calculated speeds as the CMC values for both were close to one which indicates similarity between the shapes of the waveforms (Kadaba et al. 1989) (Table 6.1, Figure 6.2). It is therefore feasible that either model could be used. However, the slightly lower RMS values of the shifted model indicates that the shifted model predicts speed data that are, on average, slightly more consistent.

In addition, if athletes and coaches wish to quantify release speeds in the training environment they should utilise the shifted model as the predicted release speeds are more accurate than those found using the non-shifted model.

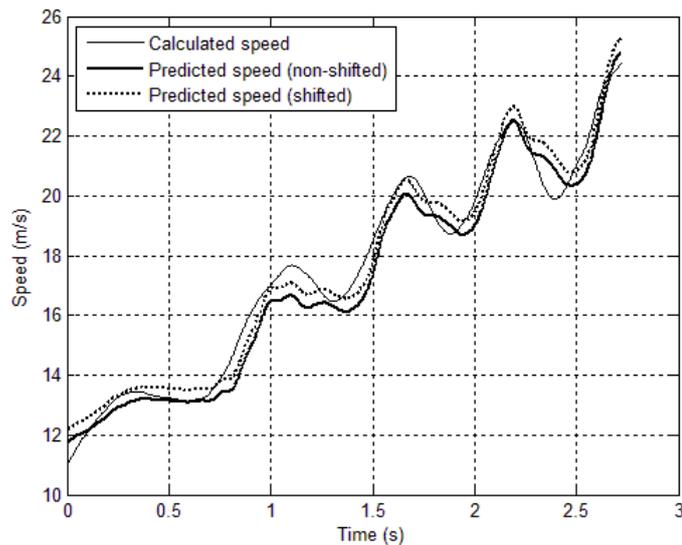


Figure 6.2. Traces of calculated speed and predicted speeds from a single trial of a male participant.

The calculated speeds exhibit simple maxima and minima behaviour (Figure 6.2). Both the measured and calculated force data also exhibit simple maxima behaviour. However, the behaviour of the measured and calculated force data in the trough regions is more complicated (Murofushi et al. 2005). There are small fluctuations present in the trough regions that are consequently observed in the predicted speed data (Figure 6.2). As a result, there is more error associated with the trough regions of the predicted speed data. This is a limitation that could potentially be an issue for athletes and coaches if they are quantifying the size of the fluctuations in the speed. In addition, there is also

error resulting from use of the strain gauge device itself. The magnitude of this error has been previously reported in the literature (Brice et al. 2008).

The regression model developed in this study is a model between velocity squared and cable force, based on equation (6.1). Implicit in this model are two assumptions, and therefore sources of error. Firstly, the model assumes that the cable force is major contributor to the centripetal force throughout the throw. Secondly, the model assumes that the velocity is determined only by the cable force, and therefore, the effect that changes in the instantaneous radius of rotation have on the velocity has been ignored. Both of these assumptions will degrade the goodness of the fit of the model. However, both assumptions have been validated given the strong correlations and relatively low RMS differences between the predicted and calculated velocities.

Time-shifting the measured force data resulted in predicted speeds that had peaks and troughs that lined up closely with the peaks and troughs in the calculated speeds. Whilst applying a time-shift to each throw reduced the effect of this time lag, it did not completely eliminate it. Athletes and coaches need to be aware of this limitation when using this type of device in the training environment. Whilst the phase lag was not completely eliminated from the predicted speeds its effect was minimized. The remaining phase lag in the predicted speeds was less than the phase lag evident in the data set of Murofushi et al. (2005). This phase lag is not an issue if the predicted speed data is the only variable being provided for feedback. However, Biomechanists will often utilise video feedback in conjunction with feedback on kinetic and kinematic variables such as speed. As a result, it is important to minimise the

phase lag here as peaks and troughs in the predicted speed data will more closely match up with the timing of the video if it is minimised.

6.6 Conclusion

This study successfully derived and validated a method that allows prediction of linear hammer speed from measured cable force data. Two linear regression models were developed and it was found that either model would be capable of predicting accurate speeds. However, data predicted using the shifted regression model were more accurate. In addition, the method proposed here accounted for the phase lag in the speed data that was evident in data presented in previous studies (Murofushi et al. 2005) that attempted to measure linear hammer speed in the training environment.

6.7 Chapter Summary

- Purpose of this study was to develop and validate a method that allows feedback on linear hammer speed during training.
- Two linear regression models that allowed prediction of hammer speed from cable force data were developed using three-dimensional positional data.

- The models were then used to predict hammer speed from directly measured cable force data and these predicted speeds were then compared with the speeds calculated from the hammer positional data to assess the level of accuracy.
- Both models were found to be capable of predicting accurate speed data.

Chapter 7 – Epilogue

7.1 Introduction

This final chapter provides a synthesis of the findings presented in the previous chapters of this thesis. Discussion about the practical applications of the findings previously presented in this thesis and recommendations for future hammer throw research are also provided.

7.2 Key findings and Implications.

7.2.1 Relationship between the linear hammer speed and the thrower applied forces

The importance of linear hammer speed at the instant of release has been highlighted on numerous occasions throughout this thesis. As the hammer speed at release is a result of how the thrower accelerates the hammer prior to release, the primary focus of this work was to investigate the speed development of the hammer during the turns. In the first study of this thesis, the relationship between the hammer's linear speed and the thrower applied cable force was investigated to identify how the magnitude and direction of the cable force affects the fluctuations in hammer speed, specifically losses in speed.

The losses in speed that occur within each turn are a result of the cable force acting at an angle behind the direction of the hammer head's radius of rotation. This is when the tangential component of the cable force is negative. The size of these speed losses are closely related to how large the tangential force is during this time ($R = -0.89, p < 0.001$).

It follows that a thrower can reduce the size of losses in speed by reducing the magnitude of the tangential force when negative or by reducing the time that negative tangential force is applied. The thrower can alter the magnitude of the tangential force by either reducing the cable force's magnitude or by altering the angle the cable force is acting at (Equation 4.2). It was found here that the most effective way to minimise the impact of negative tangential force is to reduce the angle as opposed to the time spent applying negative force. Therefore, the findings of this study suggest that a thrower should aim to make technique alterations that reduce this angle.

7.2.2 Relationship between thorax-pelvis separation angle and hammer kinetics and kinematics in the hammer throw.

The second study of this thesis was concerned with assessing motions of the thorax relative to the pelvis. Thorax-pelvis separation angle was determined and the relationships between this angle and specific hammer kinetic and kinematic parameters were investigated. Specifically, the relationships considered here were the relationships between the separation angle and the hammer kinetic

and kinematic variables identified in Study one as being the components that contribute most to speed losses.

Movement of the thrower's thorax relative to the pelvis was focused on within this study as hammer throw technique is strongly influenced by movement of the thorax (Otto, 1991, Morley, 2003). While movement of the thorax or shoulders relative to the pelvis has been discussed previously in coaching literature, it has received little research attention (Judge, Hunter & Gilreath, 2008). In addition, it was thought that thorax movement relative to the pelvis may be a variable that could be easily manipulated by the thrower, specifically when they are in the double support phase.

The results of this study indicate that throwers should aim to reduce the magnitude of the thorax-pelvis separation angle during double support, specifically during turn two and the second last turn. This was found to result in a smaller loss in speed during the subsequent single support phase.

7.2.3 Predicting linear hammer speed in the training environment

The first two studies of this thesis were concerned with assessing hammer speed development and identifying how a thrower may be able enhance this via alterations to their throwing technique. The aim of the third and final study was to develop and validate a method that would allow accurate feedback of linear hammer speed within the training environment. This would allow athletes and coaches to implement the technique changes outlined in the second study and assess how these changes affect hammer speed.

The most accurate way to determine speed is from three-dimensional positional data. However, the current methods that allow collection of this positional data do not facilitate immediate feedback in the training environment. A method was developed and validated here that allows linear hammer speed to be predicted for measured cable force. Unlike positional data, there are measurement systems reported in the literature (Brice et al. 2008, Murofushi et al. 2007, Hwang & Adrian, 1984) that allow cable force data to be measured and relayed to the athlete and coach in the training environment.

Two linear regression models were developed that allowed squared linear hammer speed to be predicted from cable force data. These models were developed using knowledge of the relationship between linear speed and centripetal force presented in Equation 6.1. One model was derived using data that were time shifted so that peaks in the force and speed data coincided (shifted model). The second model was derived using data that were not time shifted (non-shifted model).

Both models were found to be capable of predicting accurate speeds. However, data predicted using the shifted regression model were more accurate. Therefore, either model could be utilised, in conjunction with a device that allows direct measurement of cable force, to provide immediate feedback on linear hammer speed in the training environment.

7.3 Limitations and recommendations for future research.

The first two studies of this body of work were concerned with ascertaining what technique adaptations could be utilised by the thrower to enhance speed development. The major recommendation that came from this work is that throwers should aim to reduce the thorax-pelvis separation angle by as much as possible during double support. Currently, it is unknown whether a thrower can easily manipulate thorax-pelvis separation angle. It is suggested that future work could involve the development of a training study to assess if throwers can actively alter thorax-pelvis separation. In addition, future focus should also revolve around assessment of whether changes to thorax-pelvis separation angle do lead to better speed development which could be assessed via the system outlined in the third study.

Although full body three-dimensional kinematic data were collected for all ten participants, the only kinematic variable analysed here was rotation of the thorax relative to the pelvis (thorax-pelvis separation angle). The focus on thorax-pelvis separation angle here could be considered a limitation as it is highly probable that other thrower kinematic variables will also have an influence on speed development. Therefore, the relationships between other thrower kinematic variables and speed development should be considered in future studies.

The throwing ability of the ten participants utilised in the first two studies of this thesis could also be considered a limitation of this work. In these studies the average distance thrown was 54.3 ± 7.6 m for the male participants and 53.9 ± 3.2 m for the female participants which are considerably lower than the distances thrown by the world's leading athletes. Therefore, any of the findings found here can only be applied to this cohort or throwers of similar ability. Future work should consider if the relationships observed here are also consistent with the techniques of more highly skilled throwers.

7.4 Conclusion

The aims of this thesis were twofold. The first two studies focused on assessing the method of speed development in the hammer throw and identifying how a thrower could specifically reduce the size of the losses in speed that occur within each turn. It was found that, during double support, throwers should aim to reduce shoulder-pelvis separation angle by as much as possible as this results in a smaller loss in speed in the following single support phase. In the final study of this thesis a measurement system was developed and validated that would allow feedback on hammer speed within the training environment. This system was developed to allow throwers to assess how changes to their technique, based on the recommendations of the first two studies, effect the speed development.

Chapter 8 – Bibliography

Ariel, GB, Walls, RM & Penny, MA 1980, 'Biomechanical analysis of the hammer throw', *Track & Field Quarterly Review*, vol. 80, no. 1, pp. 41-51.

Asuero, AG, Sayago, A & González, AG 2006, 'The correlation coefficient: An overview', *Critical Reviews in Analytical Chemistry*, vol. 36, no. 1, pp. 41-59.

Babbitt, D 2003, 'Hammer', in J Silvester (ed.), *Complete Book of Throws*, Human Kinetics, Lower Mitcham, p. 131-158.

Bartlett, RM 1992, 'The biomechanics of the discus throw: A review', *Journal of Sports Sciences*, vol. 10, no. 5, pp. 467-510, viewed 16 January 2013, DOI:10.1080/02640419208729944 < <http://www.tandfonline.com/loi/rjsp20>>.

Bartonietz, K 1994, 'A biomechanical analysis of throws with different weight and length hammers', *Modern Athlete & Coach*, vol. 32, no. 4, pp. 33-6.

Bartonietz, K 2000, 'Hammer throwing: problems and prospects', in VM Zatsiorsky (ed.), *Biomechanics in sport: performance enhancement and injury prevention*, Blackwell Science Ltd., Oxford, vol. 4, pp. 458-86.

Bartonietz, K, Barclay, L & Gathercole, D 1997, 'Characteristics of top performances in the women's hammer throw: Basics and technique of the world's best athletes', *New Studies in Athletics*, vol. 12, no. 2, pp. 101-9, viewed 20 June 2007, <<http://194.213.2.7/wps/portal/iaaf>>.

Bartonietz, K, Hinz, L, Lorenz, G & Lunau, G 1988, 'The hammer: The view of the DVfL of the GDR on talent selection, technique and training of throwers from beginner to top level athlete', *New Studies in Athletics*, vol. 3, no. 1, pp. 39-56. Viewed 10 June 2007, <<http://194.213.2.7/wps/portal/iaaf>>.

Braddock, RD & Van Den Driessche, P 1976, 'On the stability of differential-difference equations', *The ANZIAM Journal*, vol. 19, no. 03, pp. 358-70, viewed 15 June 2013, DOI:10.1017/S0334270000001211, <<http://www.austms.org.au/ANZIAM+Journal>>

Brice, SM 2006, 'Measurement of the cable force during the hammer throw', B.Sc Hons. thesis, James Cook University, Townsville.

Brice, SM, Ness, KF, Rosemond, D, Lyons, K & Davis, M 2008, 'Development and validation of a method to directly measure the cable force during the hammer throw', *Sports Biomechanics*, vol. 7, no. 2, pp. 274-87, viewed 20 October 2009, DOI:10.1080/14763140701841902, <<http://www.tandfonline.com/loi/rspb20>>.

Chu, Y, Sell, TC & Lephart, SM 2010, 'The relationship between biomechanical variables and driving performance during the golf swing', *Journal of Sports Sciences*, vol. 28, no. 11, pp. 1251-9, viewed 15 May 2013, DOI: 10.1080/02640414.2010.507249, <<http://www.tandfonline.com/loi/rjsp20>>.

Cohen, J 1998, *Statistical power analysis for the behavioural sciences*, 2nd edn, Lawrence Erlbaum Associates, United States of America.

Connolly, H 1996, 'Hammer throw technique', *Track Coach*, vol. 136, no. Summer, pp. 20-2.

Dapena, J 1984, 'The pattern of hammer speed during hammer throw and influences of gravity on its fluctuations', *Journal of Biomechanics*, vol. 17, no. 8, pp. 553-9, viewed 10 February 2007, <<http://www.sciencedirect.com/science/journal/00219290>>.

Dapena, J 1985, 'Factors affecting the fluctuations of hammer speed in a throw', in DA Winter, RW Norman, PR Wells, KC Hayes & AE Palta (eds), *Biomechanics IX*, Human Kinetics Champaign, Illinois, vol. 4, pp. 499-503.

Dapena, J 1986, 'A Kinematic study of centre of mass motions in the hammer throw', *Journal of Biomechanics*, vol. 19, no. 2, pp. 147-58, viewed 9 February 2007, <<http://www.sciencedirect.com/science/journal/00219290>>.

Dapena, J 1989, 'Some Biomechanical aspects of Hammer Throwing', *Athletics Coach*, vol. 23, no. 3, p. 8.

Dapena, J & Feltner, ME 1989, 'Influence of the direction of the cable force and of the radius of the hammer path on speed fluctuations during hammer throwing', *Journal of Biomechanics*, vol. 22, no. 6/7, pp. 565-75, viewed 10 February 2007, <<http://www.sciencedirect.com/science/journal/00219290>>.

Dapena, J, Gutierrez-Davila, M, Soto, VM & Rojas, FJ 2003, 'Prediction of distance in hammer throwing', *Journal of Sports Sciences*, vol. 21, pp. 21-8, viewed 17 June 2007, DOI:10.1080/0264041031000070921, <<http://www.tandfonline.com/loi/rjsp20>>.

Dapena, J, Hintermeister, R, Lunt, G & Stewart, P 1982, 'Biomechanical analysis of hammer throw', in K McGill (ed.), *Report for Elite Athlete Project (USOC/TAC)*, New York, p. 58.

Dapena, J & McDonald, C 1989, 'A three-dimensional analysis of angular momentum in the hammer throw', *Medicine and Science in Sports and Exercise*, vol. 21, no. 2, pp. 206-20.

Dapena, J & Teves, MA 1982, 'Influence of the diameter of the hammer head on the distance of a hammer throw', *Research Quarterly for Exercise and Sport*, vol. 53, no. 1, pp. 78-81.

Davis III, RB, Öunpuu, S, Tyburski, D & Gage, JR 1991, 'A gait analysis data collection and reduction technique', *Human Movement Science*, vol. 10, no. 5, pp. 575-87, viewed 20 January 2013,

<<http://www.sciencedirect.com/science/journal/01679457>>

De Mestre, N 1990, *The Mathematics of Projectiles in Sport*, Cambridge University Press, Cambridge.

Dowlan, S 2003, *Vicon Equipment Protocol*, Australian Institute of Sport, Canberra.

Erdfelder, E, Faul, F & Buchner, A 1998, 'GPOWER: A general power analysis program', *Behavior Research Methods, Instruments, & Computers*, vol 28, no. 1, pp. 1-11, viewed May 22 2014, <<http://link.springer.com/journal/13428>>.

Gutierrez, M, Soto, VM & Rojas, FJ 2002, 'A biomechanical analysis of the individual techniques of the hammer throw finalists in the Seville Athletics World Championships 1999', *New Studies in Athletics*, vol. 17, no. 2, pp. 15-26, viewed February 9 2007, <<http://194.213.2.7/wps/portal/iaaf>>.

Hill, AV 1922, 'The maximum work and mechanical efficiency of human muscles, and their most economical speed ', *Journal of Physiology*, vol. 56, no. 1-2, pp. 19-41.

Hopkins, WG 2006, 'A Scale of Magnitudes for Effect Statistics', in *A new view of statistics*, viewed 4 May 2010,
<<http://sportsci.org/resource/stats/effectmag.html>>.

Horan, SA, Evans, K, Morris, NR & Kavanagh, JJ 2010 'Thorax and pelvis kinematics during the downswing of male and female skilled golfers', *Journal of Biomechanics*, vol. 43, no. 8, pp. 1456-62. viewed 15 January 2013, DOI 10.1016/j.jbiomech.2010.02.005 <<http://www.jbiomech.com/>>.

Hubbard, M 1989, 'The throwing events in track and field', in CL Vaughan (ed.), *Biomechanics of Sport*, CRC Press Inc., Boca Raton, Florida, p. 23.

Hubbard, M 2000, 'The flight of sports projectiles', in VM Zatsiorsky (ed.), *Biomechanics in sport: performance enhancement and injury prevention*, Blackwell Science Ltd., Oxford, vol. 4, p. 381-400.

IAAF 2010, *IAAF Competition rules 2010-2011*, viewed 12 January 2011,
<<http://www.iaaf.org/competitions/technical/regulations/index.html>>.

IAAF 2013, *IAAF world records and lists*, viewed 24 April 2013,
<<http://www.iaaf.org/records/toplists>>.

Jabs, R-G 1979, 'Velocity in hammer throwing', *Track Technique*, vol. 77, no. Fall, pp. 2449-50.

Jaede, E 1991, 'The main elements of modern hammer throwing technique', *Modern Athlete and Coach*, vol. 29, no. 3, pp. 16-9.

Johnson, C 1969, *Hammer throwing*, British Amateur Athletic Board, London.

Johnson, RA & Wichern, DW 2007, *Applied multivariate statistical analysis*, Prentice Hall, Upper Saddle River.

Judge, L 2000a, 'A Technique Analysis of the Hammer Throw for Men & Women: Part 1', *Coach & Athletic Director*, vol. 69, no. 7, pp. 36-9.

Judge, L 2000b, 'A Technique Analysis of the Hammer Throw for Men & Women: Part 2', *Coach & Athletic Director*, vol. 69, no. 8, pp. 46-51.

Judge, LW, Hunter, I & Gilreath, E 2008, 'Using Sport Science to Improve Coaching: A Case Study of the American Record Holder in the Women's Hammer Throw', *International Journal of Sports Science & Coaching*, vol. 3, no. 4, pp. 477-88, viewed 16 April 2010, <<http://contentdm.lib.byu.edu/cdm/ref/collection/IR/id/1349>>.

Kadaba, MP, Ramakrishnan, HK, Wootten, ME, Gainey, J, Gorton, G & Cochran, GVB 1989, 'Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait', *Journal of Orthopaedic Research*, vol. 7, no. 6, pp. 849-60., viewed 19 January 2013, DOI: 10.1002/jor.1100070611, <[http://onlinelibrary.wiley.com/journal/10.1002/\(ISSN\)1554-527X](http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1554-527X)>.

Kwon, Y-H, Han, KH, Como, C, Lee, S & Singhal, K 2013, 'Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers', *Sports Biomechanics*, vol. 12, no. 3, pp. 231-46. viewed 20 May 2013, DOI:10.1080/14763141.2013.771896, <<http://www.tandfonline.com/loi/rspb20>>.

Leigh, S, Gross, MT, Li, L & Yu, B 2008, 'The relationship between discus throwing performance and combinations of selected technical parameters', *Sports Biomechanics*, vol. 7, no. 2, pp. 173-93, viewed 20 May 2013, DOI:10.1080/14763140701841399, <<http://www.tandfonline.com/loi/rspb20>>.

Leigh, S & Yu, B 2007, 'The associations of selected technical parameters with discus throwing performance: A cross-sectional study', *Sports Biomechanics*, vol. 6, no. 3, pp. 269-84. viewed 20 May 2013, DOI:10.1080/14763140701489744, <<http://www.tandfonline.com/loi/rspb20>>.

Lichtenberg, DB & Wills, JG 1978, 'Maximizing the range of the shot put ', *American Journal of Physics*, vol. 46, no. 5, pp. 546-9. DOI:10.1119/1.11258, <<http://scitation.aip.org/content/aapt/journal/ajp>>.

Maheras, AV 2009, 'Reassessing velocity generation in hammer throwing', *New Studies in Athletics*, vol. 24, no. 4, pp. 71-80, viewed 15 March 2011, <<http://194.213.2.7/wps/portal/iaaf>>.

Maroński, R 1991, 'Optimal distance from the implement to the axis of rotation in hammer and discus throws', *Journal of Biomechanics*, vol. 24, no. 11, pp. 999-1005, viewed 10 March 2008, <<http://www.sciencedirect.com/science/journal/00219290>>.

Mayagoitia, RE, Nene, AV & Veltink, PH 2002, 'Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems', *Journal of Biomechanics*, vol. 35, no. 4, pp. 537-42, viewed 15 April 2013, DOI:10.1016/S0021-9290(01)00231-7, <<http://www.jbiomech.com/>>.

Morley, M 2003a, 'Hammer throwing - the delivery part 1', *The Coach*, vol. 18, no. September/October, pp. 28-32.

Morley, M 2003b, 'Hammer throwing - the turns part 1', *The Coach*, vol. 16, no. May/June, pp. 21-5.

Morriss, CJ & Bartlett, RM 1992, 'Biomechanical analysis of the hammer throw', *Athletics Coach*, vol. 126, no. 3, pp. 11-7.

Morriss, CJ & Bartlett, RM 1995a, 'Biomechanical analysis of the men's hammer throw', in RM Bartlett (ed.), *Biomechanical analysis of the 1995 national championships*, British Athletic Federation, Alsager, vol. 1, pp. 1-22.

Morriss, CJ & Bartlett, RM 1995b, 'Biomechanical analysis of the women's hammer throw', in RM Bartlett (ed.), *Biomechanical Analysis of the 1995 National Championships*, British Athletic Federation, Alsager, vol. 1, pp. 1-20.

Murofushi, K, Sakurai, S, Umegaki, K & Kobayashi, K 2005, 'Development of a system to measure radius of curvature and speed of hammer head during turns in hammer throw', *International Journal of Sport and Health Science*, vol. 3, pp. 116-28, viewed 15 August 2008, DOI:10.5432/ijshs.3.116, <<https://www.jstage.jst.go.jp/browse/ijshs>>.

Murofushi, K, Sakurai, S, Umegaki, K & Takamatsu, J 2007, 'Hammer acceleration due to thrower and hammer movement patterns', *Sports Biomechanics*, vol. 6, no. 3, pp. 301-14, viewed 10 January 2008, DOI:10.1080/14763140701489843, <<http://www.tandfonline.com/loi/rspb20>>.

Myers, J, Lephart, S, Tsai, Y-S, Sell, T, Smoliga, J & Jolly, J 2008, 'The role of upper torso and pelvis rotation in driving performance during the golf swing', *Journal of Sports Sciences*, vol. 26, no. 2, pp. 181-8, viewed 10 May 2013, DOI:10.1080/02640410701373543, <<http://www.tandfonline.com/loi/rjsp20>>.

Okamoto, A, Sakurai, S & Ikegami, Y 2007, 'How the body weight affect the pulling force in hammer throw?', *Journal of Biomechanics*, vol. 40, no. Supplement 2, p. S621, viewed 20 November 2008, <<http://www.jbiomech.com/>>.

Ohta, K, Umegaki, K, Murofushi, K & Luo, Z 2010, 'Analysis of hammer movement based on a parametrically excited pendulum model', *Procedia Engineering*, vol. 2, no. 2, pp. 3197-203, viewed 30 June 2011
DOI:10.1016/j.proeng.2010.04.132
<<http://www.sciencedirect.com/science/journal/18777058>>.

Otto, RM 1991, 'A kinematic analysis of Yuriy Sedikh's world record hammer throw',
Modern Athlete and Coach, vol. 29, no. 4, pp. 3-8.

Pagani, T 1980, 'Hammer throw technique', *Track & Field Quarterly Review*, vol. 80,
no. 1, pp. 30-1.

Riley, ZA & Doyle, TLA 2005, 'Lack of research hinders evolution of hammer throw',
Biomechanics, vol. 12, no. 2, pp. 51-6.

Rojas-Ruiz, FJ & Gutierrez-Davila, M 2009, 'The relation between angular
displacement of the hammer in the double support phase and its velocity in the
hammer throw', *Journal of Human Sport & Exercise*, vol. 4, no. 3, pp. 254-61,
viewed 10 January 2010 DOI:10.4100/jhse.2009.43.07,
<<http://www.jhse.ua.es/jhse>>.

Samozvetsov, A 1980, 'Acceleration of the Hammer', in J Jarver (ed.), *The Throws*,
Tafnews Press, Los Altos, California, p. 152-155.

Sanderson, LK, McClements, JD & Gander, RE 1991, 'Development of apparatus to
provide immediate accurate feedback to sprinters in the normal training
environment', *New Studies in Athletics*, vol. 6, no. 2, pp. 33-41, viewed 10
February 2012, <<http://194.213.2.7/wps/portal/iaaf>>.

Simonyi, G 1980, 'Notes on the technique of hammer throwing', *Track & Field Quarterly review*, vol. 80, no. 1, pp. 29-30.

Susanka, P, Stepanek, J, Miskos, G & Terauds, J 1987, 'Hammer-Athlete relationship during the hammer throw', in J Terauds, BA Gowitzke & LE Holt (eds), *International Symposium of Biomechanics in Sports*, Del Mar, California, vol. 4, pp. 194-200.

Tancred, P & Carter, CA 1980, *Athletic Throwing*, Faber and Faber Limited, London.

Tutevich, VN 1969, *Teorija sportivnych metanij. [Theory of the throwing events]*, Fizkultura i Sport, Moscow.

Winter, DA 2009, *Biomechanics and motor control of human movement*, 4th edn, John Wiley & Sons, Inc., Hoboken.

Woicik, M 1980, 'Hammer throw', *Track & Field Quarterly Review*, vol. 80, no. 1, pp. 23-6.

Appendices

Appendix A: Participant Information Sheet and Informed Consent Form.



PARTICIPANT INFORMATION

A detailed biomechanical analysis of the hammer throw: Using direct measurement techniques to carry out analyses on elite and sub-elite throwers

Researcher

Mrs Sara Brice^{1,2}

Supervisors

Dr Kevin Ness¹, Adjunct Professor Keith Lyons², Mr Doug Rosemond² and Dr Ronald White¹

¹ School of Maths Physics and Information Technology, James Cook University, Townsville, Australia

² Biomechanics and Performance Analysis Department, Australian Institute of Sport, Canberra, Australia

Project Aim

A recently completed validation study carried out with hammer throw athletes and coaches at the Australian Institute of Sport (AIS) involved the mounting of a strain gauge on the hammer wire for the purpose of obtaining cable force data throughout a throw. This research showed the cable force data obtained from the strain gauge unit was an accurate method for measuring cable force throughout the throw.

It is proposed to use this system to collect data from both elite and sub-elite throwers in order to obtain a better understanding of how the development of the cable force during the turns of the hammer throw affects the release velocity and throw distance. A system will also be developed to identify the relevant kinematic variables of the hammer throw. These systems will also enable the immediate feedback on these variables and the cable force to athletes and coaches in the training environment.

General outline of the Project and Participant involvement

A mixture of elite and sub-elite male and female hammer athletes will be asked to take part in this study. They will be given a consent form to sign. They will be asked to carry out 10 trials with an instrumented hammer while being captured with a 22 camera Vicon infrared motion analysis system. The data will be used for full body 3D kinematic analyses.



Each hammer wire will be instrumented with a single strain gauge which is mounted on the wire. A small connector will be attached to the gauge which will connect to a thin wire that will run up the subjects arm and down their back to a small box that will contain the gauge amplifier. The wire carries 4 volts and carries negligible current. Before each throw the strain gauge will be calibrated using a previously developed calibration rig.

Before each subject begins their training session they will have infrared retro-reflective markers positioned on important anatomical land marks. Once the subject has completed their usual warm-up they will perform 10 throws with an instrumented hammer wire and will be captured with the Vicon infrared cameras. From the captured footage 3D full body analyses will be carried out to determine the relevant kinematic variables of the hammer throw.

During each throw the cable force will be collected simultaneously using Bluetooth technology. These data will then be overlaid on video footage which will be captured with a computer from a Sony digital camera positioned behind the hammer cage. This will be provided to the subject and their coach (if present) for instantaneous feedback. The distance of each throw will be measured for later comparison.

Once the relevant kinematic variables have been determined a further round of testing will be carried out with a larger number of subjects. A comparison of the cable force will be made between each subject's throws which will then be compared with other subjects' data. A conclusion on what is the optimal force-time relationship and the optimal magnitude of the cable force will be found. Comparisons between the kinematic variables for each subject will be made as well.

It is hoped that these measurement systems can be used to prove or disprove the biomechanical community's current theories on what the key parameters for the hammer throw are and ignite academic and technical debate.

Discomfort/Risks and Exclusion/Inclusion criteria

The potential risks during data collection are no greater than those experienced during a normal training session. You are free to withdraw consent and to discontinue participation in the project at any time.

Subjects will be asked to perform with their normal technique and will throw standard competition weight hammers. If a subject is unable to do this then they will not be considered for this study.



Confidentiality/Anonymity and Data Storage

As a participant you will be given the option of whether you would like your data and video footage to be stored under your name so that future comparisons between data can be undertaken, if you do not want this all data will be stored under a subject number.

For all publishing purposes subject numbers will be used to maintain confidentiality. All data that will be collected will be stored on a computer at the Australian Institute of Sport that requires a password to access.

Ethics Committee Clearance

This project has been approved by the Human Ethics Sub-Committee of James Cook University and the Ethics Committee from the Australian Institute of Sport.

Queries and Concerns

If you have any further queries or concerns about this research project then please contact Sara Brice, Kevin Ness or Doug Rosemond:

Sara Brice

(02) 6214 7898

sara.brice@jcu.edu.au

Kevin Ness

(07) 4181 4127

kevin.ness@jcu.edu.au

Doug Rosemond

(02) 6214 1618

If you have any concerns with respect to the conduct of this study, you may contact the Secretary of the AIS Ethics Committee (Mr John Williams) on (02) 6214 1816 or contact the James Cook University Human Ethics Sub-Committee:

JCU Ethics Administrator

Tina Langford

Research Office

James Cook University

Townsville

QLD, 4811

Ph: (07) 4781 4342

Fax: (07) 4781 5521

tina.langford@jcu.edu.au



INFORMED CONSENT FORM

PRINCIPAL INVESTIGATOR Sara Brice

PROJECT TITLE: *A detailed biomechanical analysis of the hammer throw: Using direct measurement techniques to carry out analyses on elite and sub-elite throwers.*

SCHOOL *School of Maths, Physics and Information Technology*

CONTACT DETAILS **Sara Brice**
Biomechanics and Performance Analysis Dept
Australian Institute of Sport
PO Box 176
Belconnen ACT 2616
Ph 02 6214 7898
Mob 0421 188 555
Email sara.brice@ausport.gov.au

JCU CONTACT DETAILS: **Dr Kevin Ness** (Supervisor)
School of Maths, Physics and Information Technology
James Cook University
Townsville, Qld. 4811
Ph 07 4781 4127

Email kevin.ness@jcu.edu.au

As a participant you will be asked to carry out 10 throws with an instrumented hammer while wearing retro-reflective markers on anatomical landmarks.

The instrumented hammer consists of a competition weight hammer that has a strain gauge mounted on the wire. You will wear a belt that will have a small box on it. A thin wire will run up your back, from the box, to your shoulder and down your arm to your wrist. A small connector will be attached to the gauge that will connect to the wire at the wrist and disconnects upon release.

A 22 camera Vicon infrared motion analysis system will be used to capture data for each throw. From the captured data it will be determined what are the important kinematic variables of the hammer throw.

The potential risks for the thrower during data collection are no greater than those experienced during a normal training session. You are free to withdraw consent and to discontinue participation in the project at any time.



The aims of this study have been clearly explained to me by Sara Brice and I understand what is required of me. I know that taking part in this study is voluntary and I am aware that I can stop taking part in it at any time and may refuse to answer any questions.

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 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 any information I give will be kept strictly confidential and that no names will be used to identify me with this study without my approval.

Name: <i>(printed)</i>	
Keep data under my name for comparison if similarly tested at a later date <input type="checkbox"/>	Keep data under non referential numbering system <input type="checkbox"/>
Signature:	Date:
Guardian Signature:	Date:

WITNESSED BY RESEARCHER OBTAINING CONSENT

Name: <i>(printed)</i>	
Signature: <i>(Principal Investigator)</i>	Date:

Appendix B: Publication of Chapter 4

This Appendix contains the manuscript of the paper relating to Chapter 4 of this thesis. This paper has published in *Sports Biomechanics*:

Brice, S. M., Ness, K. F., & Rosemond, D. (2011). An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers. *Sports Biomechanics*, 10, 174-184. doi:10.1080/14763141.2011.592210

Title: An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers.

Keywords: applied, force, hammer, speed

Author list: Sara M. Brice^{1,2}, Kevin F. Ness¹ & Doug Rosemond²

¹School of Engineering and Physical Sciences, James Cook University

²Australian Institute of Sport Movement Science – Biomechanics

Acknowledgement:

The authors wish to thank staff of the Biomechanics and Performance Analysis Discipline of the Australian Institute of Sport Movement Science Department for their assistance with the data collection for this study.

Abstract

The purpose of this study was to investigate the relationship between the cable force and linear hammer speed in the hammer throw and to identify how the magnitude and direction of the cable force effects the fluctuations in linear hammer speed. Five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) throwers participated and were required to perform ten throws each. The hammer's linear velocity and the cable force and its tangential component were calculated via hammer head positional data. As expected a strong correlation was observed between decreases in the linear hammer speed and decreases in the cable force (normalised for hammer weight). A strong correlation was also found to exist between the angle by which the cable force lags the radius of rotation at its maximum (when tangential force is at its most negative) and the size of the decreases in hammer speed. These findings indicate that the most effective way to minimise the effect of the negative tangential force is to reduce the size of the lag angle.

Introduction

A hammer throw in competition consists of preliminary swings/winds followed most commonly by three or four turns or on rare occasions five turns and then the release of the hammer. Each individual turn consists of a phase of single (one foot on the ground) and double (both feet on the ground) support. Past research suggests that athletes should ensure that more time is spent in double support than single support as the athlete can accelerate the hammer most effectively in double support (Bartoniets, Barclay & Gathercole (1997); and overview by Bartoniets, 2000).

Given the projectile nature of the hammer after release the speed of the hammer at release is the most important release parameter and it is crucial it be as large as possible (Jabs, 1979; Dapena, 1984, 1985; Bartoniets, 2000). The acceleration to maximum speed is affected by the forces acting on the hammer and by the time interval that these forces act over. If aerodynamic forces are ignored, the forces acting are gravity and the force applied by the thrower through the cable (cable force) to the hammer's head. At any instant, these forces can be decomposed into three components (see Figure 1); normal, radial and tangential to the instantaneous circle of rotation (Tutevich (1969), Dapena, 1984). For a given hammer mass, the normal component has no effect on the hammer's linear speed while the radial component contributes to the radial acceleration of the hammer head which in turn determines the radius of curvature. The component affecting the instantaneous linear hammer speed (hammer speed) is the tangential component (tangential force) which acts in either the same or opposite direction to the linear hammer velocity, depending on whether the cable force is acting at an angle in front of or behind the direction of the radius of rotation of the hammer's head. Given this relationship between tangential force and speed development it is essential that athletes and coaches have a strong understanding of how this force acts during the throw.

Recently there has been increasing amounts of research into the acceleration mechanism of the hammer (Maheras, (2009); Murofushi, Sakurai, Umegaki & Kobayashi (2005); Murofushi, Sakurai, Umegaki & Takamatsu (2007); Ohata, Umegaki, Murofushi & Luo (2010)). Murofushi and colleagues (2005) developed an instrumented hammer that provided information on hammer speed and radius of curvature in a short amount of time. They suggested that this system could be used to increase training effectiveness as it allows for interpretation of this information soon after the throw is completed.

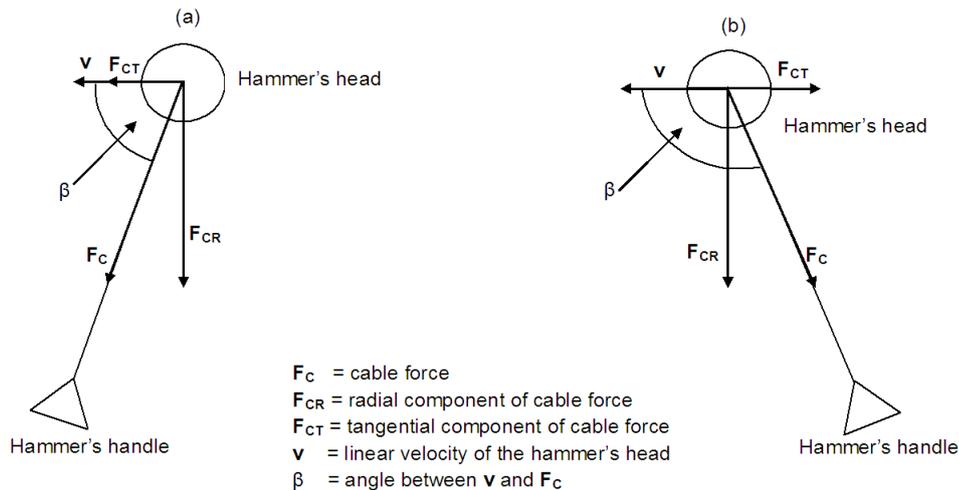


Figure 1. Radial and tangential components of the cable force when the cable force vector is pulling in front of the direction of the radius of rotation (a) and when it is pulling behind (b). The normal component would be perpendicular to the plane of motion in both (a) and (b) and would be pointing upwards if the cable force vector is acting above the plane of rotation. Conversely, the normal component would be pointing downwards if the cable force vector is acting below the plane of rotation.

While this recent literature has allowed good insight into the acceleration mechanism there is still little in the literature that specifically investigates the tangential force and its effect on the hammer speed. Susanka and Colleagues (1987) found that for a 79.22 m throw by former Soviet hammer thrower Yuriy Sedykh (current world record holder) in the final two turns the tangential force fluctuates between ± 500 N twice per turn. Another study by Bartonietz (1994) presented data from a 82.34 m throw by the same athlete that showed that throughout the throw, the tangential force fluctuated in polarity between approximately -150 N and 200 N once per turn. Dapena and Feltner (1989) investigated the influence of the direction of the cable force on fluctuations in hammer speed and found the fluctuations not due to gravity were caused by the positive and negative fluctuations in the tangential force. While Dapena and Feltner (1989) reported this finding no inferences were made about the strength of this relationship or how this relationship could be used specifically to reduce the size of losses in hammer speed.

The purpose of this cross-sectional investigative study was to quantify the strength of the relationship between cable force and hammer speed and identify how the magnitude and direction of the cable force affects the fluctuations in hammer speed. Specifically, this was to determine which element of the cable force's tangential component is most closely related to losses/gains in the hammer speed, given that these losses/gains occur when the polarity of the tangential force is negative/positive. Investigation into how athlete performance can be improved in relation to cable force application was carried out.

Methods

Five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) hammer throwers of varying ability participated in this study. Each participant used a three ($n = 2$), four ($n = 7$) or five turn ($n = 1$) throwing style. Each participant was in the competition phase of the Australian domestic athletics season at the time of data collection for this study. All participants gave written informed consent to participate in this study which was given ethical approval by the James Cook University Human Ethics Committee and the Australian Institute of Sport Ethics Committee.

The data collection for this study was carried out at a surveyed outdoor track and field facility and all throw distances were measured in accordance with the International Association of Athletics Federations (governing body of the sport) competition protocols (IAAF, 2009). Participants were asked to complete ten throws as part of this study with a competition standard hammer (7.26 kg for males and 4 kg for females) with retro-reflective tape (markers) positioned on the hammer's cable at known distances from the centre of the hammer's head. Prior to data collection each participant was allowed to complete their usual warm up procedures.

A 21 infra-red camera system (Oxford Metrics, Oxford, UK) sampling at a frame rate of 250 Hz was used to record the positions of the markers on the hammer's cable throughout each of the participant's ten throws. The cameras were positioned at varying heights around the throwing circle to ensure that the markers could be seen at all times and the volume where the hammer throw activity took place was dynamically calibrated using the calibration functions in the Vicon Nexus software suite (Oxford metrics, Oxford UK). The origin was set approximately at the centre of the throwing circle with the y axis aligned with the direction of the throw, the z axis defined as being in the vertical direction and the x axis defined as being perpendicular to the y and z axes. Testing was completed after twilight conditions as infra-red cameras were used.

The collected video footage of the throws were post processed in Vicon Nexus where any gaps in marker trajectory were filled using a pattern or spline fit. All trajectories were filtered using a Woltring (spline) filter with a mean standard error (MSE) of 15. This MSE was determined to be the optimal filter level following a Fourier and residual analysis (Winter, 2005).

Once the data were filtered the positional data of the markers were then used, along with direction cosines, to determine the position of the hammer's head for each throw from entry through to release. Entry was defined as being the point in the throw, just prior to the start of the turns, when the hammer passed through 90° (right handed thrower) or 270° (left handed thrower) where the 0° was aligned with the negative y axis and 180° was aligned with the positive y axis. Release was defined as being the instant in time when separation was detectable between the hands and the hammer's handle and was measured by comparing the distance between markers on the participant's hands and the marker on the hammer's cable that was closest to the hands. The hammer head

positional data were then used to determine the linear velocity of the hammer, and the cable force and its tangential component (Figure 1). The cable force was determined from

$$\mathbf{F}_c = m \left(\frac{d^2 \mathbf{s}}{dt^2} - \mathbf{g} \right) \quad (1)$$

Where m is the mass of the hammer (7.26 kg for males; 4 kg for females), \mathbf{s} is the three dimensional position of the hammer's head at any time t and \mathbf{g} is the gravity vector (approximately -9.80 m/s^2 in the vertical direction which is defined as the z direction in this study). The magnitude of the tangential force was calculated using

$$F_{c_T} = F_C \cos \beta \quad (2)$$

where β is the angle between the cable force and the hammer linear velocity vectors. The tangential force is positive when $\beta < 90^\circ$ and negative when $\beta > 90^\circ$. All calculations were carried out using the Matlab software suite (The Mathworks, Natick, USA).

Traces of the calculated kinetic and kinematic parameters, along with the vertical position of the hammer's head and when double and single support phases occurred, were produced for comparison with previously reported data in the literature. This was also done to build an understanding of when certain behaviour such as maxima and minima of the focus variables were occurring. The magnitude of the angle between the hammer velocity vector and the cable force vector and its behaviour was also investigated as it and the magnitude of the cable force affects the magnitude and direction of the tangential force which is responsible for increases and decreases in hammer speed.

All cable force and tangential force data that were used in the correlation analyses were normalised by dividing by the weight of the hammer that was used. This was done as the two genders use different weight hammers and was required so that all male and female data could be combined for the correlation analyses. Scattergrams were also produced and examined to check the validity of combining gender data for the correlation analyses. As the throws were by athletes of different gender and performance level, correlations between the size of the decreases in the cable force, tangential force and the hammer speed were calculated to assist with gaining an understanding of how these variables were related. Only the decreases were investigated in this study as the main purpose was to ascertain the cause of losses in hammer speed. All correlations were classified using the definitions described by Hopkins (2006).

It was expected that analyses of the preceding correlations would assist with identifying how the magnitude and direction of the cable force directly effects hammer speed, particularly losses in hammer speed. This was done to ascertain whether an athlete should alter the magnitude of the cable force or the angle it acts at so as to reduce the detrimental effect the tangential force has on hammer speed when its polarity is negative.

Results

Averages for each gender in release speed, distance thrown, best distance thrown, peak cable force and peak cable force normalised for hammer weight are shown in Table I to give some indication of the skill level of the participants in the study. The magnitudes of the peaks in normalised cable force are almost the same across genders (Table I) and comparison between peak normalised cable force and distance thrown shows there is a near perfect correlation between the two ($R = 0.94$, $p < 0.0001$).

Table I. Gender averages of distance thrown, distance of best throw produced, release speed, peak cable force and peak force normalised for hammer weight in this study. Standard deviations indicated in brackets.

Gender	Average throw distance (m)	Best throw (m)	Release speed (m/s)	Peak force (N)	Peak force (normalised)
Male	54.3 (7.6)	57.1 (8.4)	23.7 (1.8)	2399 (292)	33.74 (4.11)
Female	53.9 (3.2)	56.4 (2.3)	24.1 (0.7)	1376 (63.4)	35.12 (1.62)

The hammer speed, cable force, tangential force and vertical position of the hammer's head, for four different participant's best throw, are shown in Figures 2, 3 and 4 respectively. The hammer speed and cable force increased throughout each throw with a fluctuation (peak and trough) occurring in each turn and just prior to hammer release (Figures 2 and 3). The tangential force displays periods of both positive and negative values (Figure 4). The periods of negative tangential force occur during the early stages of single support with the tangential force being at its most negative around the centre of single support as the hammer approaches its highest point. These periods also coincide with decreasing hammer speed (Figure 2). The troughs in the tangential force became progressively more negative as the throw progressed while generally the peaks remained at approximately the same magnitude.

A comparison between the size of the decreases in both the cable force and its tangential component was also carried out to ascertain how a reduction in the size of the cable force decreases would affect its tangential component. It was found that the size of the decreases in normalised cable force and normalised tangential force are highly related ($R = 0.79$, $p < 0.0001$, Figure 5(a)).

The relationship between the tangential force and hammer speed was also considered. Losses in hammer speed occurred when the tangential force was negative in polarity. For this reason the relationship between the size of the loss in hammer speed reduction and the corresponding amount of time that the tangential force was negative was investigated. A statistical analysis shows that the amount of time spent applying negative tangential force is not highly related to the size of the loss in hammer speed ($R = 0.39$, $p < 0.0001$, Figure 5(b)). However, it was found that the magnitude of normalised tangential force at its most negative was highly related to the size of the corresponding reduction in hammer speed ($R = -0.89$, $p < 0.0001$, Figure 5(c)).

The magnitude of angle between the cable force vector and the hammer velocity vector at its maximum in each turn (tangential force at its most

negative) and the corresponding size of the decrease in hammer speed were compared. They were found to be very strongly related ($R = 0.87$, $p < 0.0001$, Figure 5(d)).

Within each turn the relationship between the magnitude of normalised cable force, when the angle between it and the hammer velocity vector is at its maximum, and the corresponding loss in hammer speed was also investigated. There was a moderate relationship observed between the two ($R = 0.52$, $p < 0.0001$, Figure 5(e)).

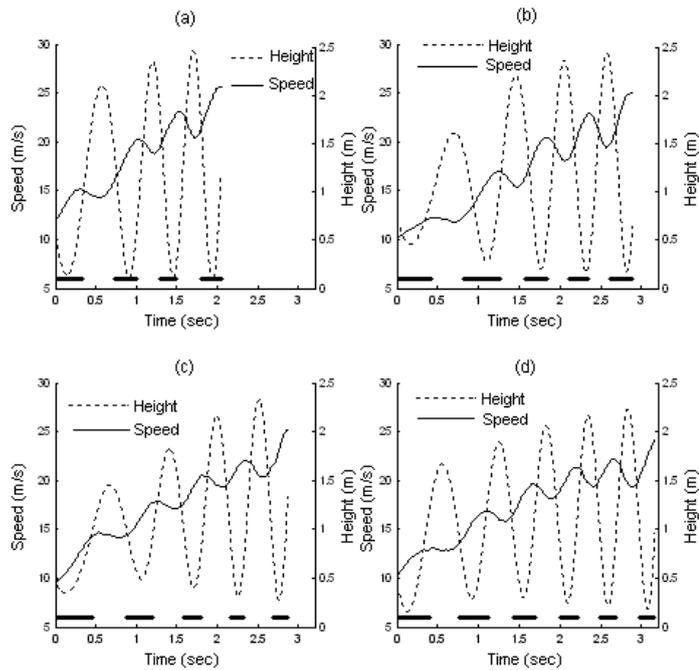


Figure 2. Graph of hammer speed and vertical height of the hammer's head from entry through to release for the best throw of: (a) male three turn thrower (63.22 m), (b) male four turn thrower (61.45 m), (c) female four turn thrower (59.86 m) and (d) female five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete is in double support.

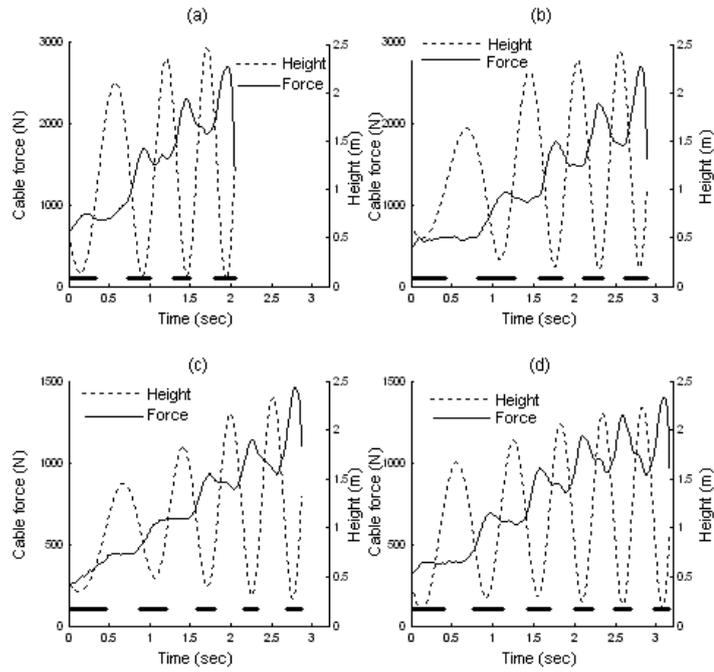


Figure 3. Graph of the magnitude of the cable force and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 2.

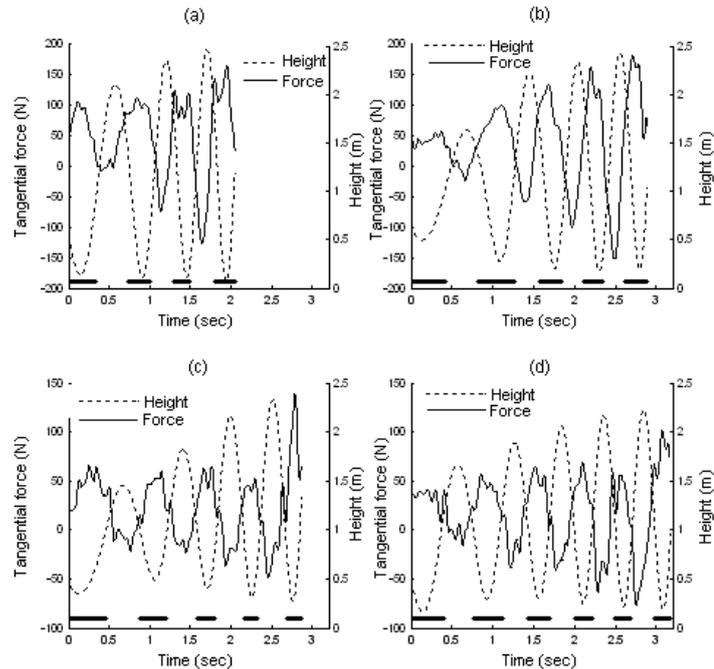


Figure 4. Graph of the tangential component force and vertical height of the hammer's head from entry through to release for the best throw of four participants; conditions same as in Figure 2.

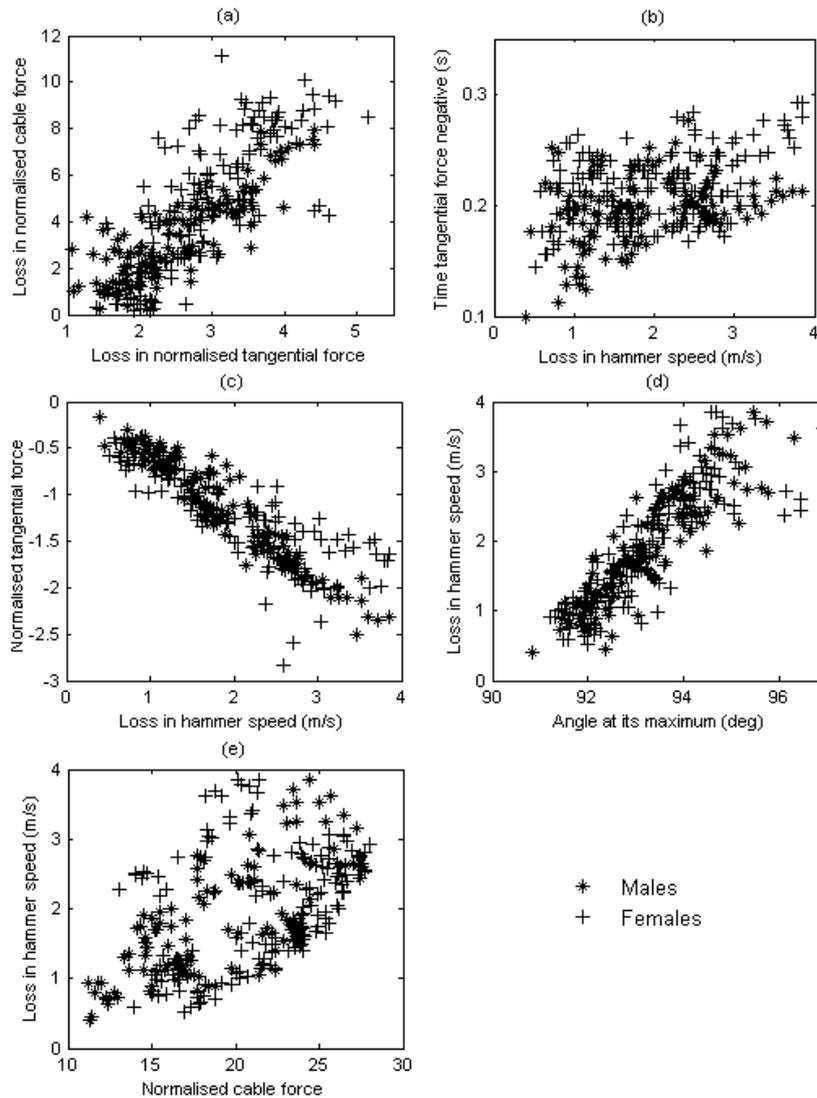


Figure 5. Scattergrams of data used to obtain the correlates in this study: (a) size of the decreases in normalised cable force vs. size of decreases in normalised tangential force, (b) time spent applying negative tangential force vs. size of the loss in hammer speed, (c) magnitude of normalised tangential force at its most negative vs. the size of the corresponding loss in hammer speed, (d) size of the decrease in hammer speed vs. the magnitude of the angle between the cable force vector and the radius of rotation at its maximum in each turn (e) losses in hammer speed vs. the magnitude of normalised cable force, when the angle between it and the radius of rotation is at its maximum within each turn.

Discussion and Implications

The general trends of the traces of hammer speed and cable force (Figures 2 and 3) are similar to those previously observed in the literature (Dapena, 1984; Bartonietz et al., 1988; Murofushi et al., 2005; Brice et al., 2008) with the males obtaining higher cable force magnitudes than the females. The trends of the traces of tangential force (Figure 4) are similar to the trend reported by Bartonietz (1994) with the polarity alternating between being positive and negative and there being a single fluctuation within each turn. However the trends observed here are quite different to the trend reported by Susanka and Colleagues (1987). The data they presented showed that the tangential force in each of the final two turns had two fluctuations between positive and negative values whereas all subjects in this current study had a single fluctuation. In addition these fluctuations varied between ± 500 N, which is approximately three times the size of the oscillations in the current study. The data presented by both Susanka and Colleagues (1987) and Bartonietz (1994) are from the same athlete (current world record holder Yuriy Sedykh). The basic shape of the tangential force trace shown by Bartonietz (1994) agrees with that in the current study; however the magnitude of the peaks is approximately 30% larger than that of the males in this study, reflecting the greater throw distance. The reason for the large differences between the two data sets is unknown however the hammer speed data presented by Susanka and Colleagues (1987) was also questionable. In particular, they observed a loss and increase in hammer speed during the delivery phase which has not been previously reported in the literature could which leads to questions relating to the integrity of their data. The regions of negative tangential force indicate when the hammer's head is leading the athlete and alternately the regions of positive tangential force indicate when they are pulling in front. There are also secondary oscillations observed in the positive peak regions of the tangential force traces which may reflect instabilities in the hammer-thrower system as the athlete attempts to accelerate the hammer. These secondary oscillations are particularly noticeable in the last two turns of the three turn throwers who have less time to accelerate the hammer and are possibly more susceptible to instability as the speed of the hammer approaches its maximum.

The mechanical relationship that exists between cable force and hammer speed alone would suggest that reducing the size of the losses in cable force that occur within each turn would lead to a reduction in the size of the corresponding decreases in hammer speed. Ideally there should be no loss in hammer speed and cable force. However, these decreases in speed and force occur during single support when the hammer head is approaching its highest position in the turn and it may be impractical to eliminate them completely due to the reduced stability of the body associated with being in single support. Gravity will also increase or decrease the hammer speed, depending upon whether the hammer is decreasing or increasing in height, respectively. The effect of gravity on speed fluctuation has been investigated by Dapena (1984), who found that its effect was significantly smaller than that of the cable force.

The relationship between hammer speed and cable force has important implications for the athlete in the training environment. Methods have been developed that allow direct and accurate measurement of the magnitude of the cable force in the training environment that also cause minimal change to the weight of the hammer (the mass of a strain gauge is added to the system which is negligible compared to systems that added 1.3 kg (Hwang and Adrian, 1984) and 0.37 kg (Murofushi et al., 2005)) and allow immediate feedback on the trend of the cable force (Brice et al., 2008). This type of feedback would allow the coach and athlete to formulate a basic assessment of an individual's performance characteristics. For example, previous studies in the literature have shown that generally each peak in hammer speed and cable force is clearly greater in magnitude than the previous peak (Dapena, 1984; Bartonietz et al., 1988; Murofushi et al., 2005; Brice et al., 2008). In this current study this type of behaviour was observed in all but one female (four turner) participant's data. In the case of this participant, comparison between the peaks in hammer speed and cable force in final two turns of her best throw showed only small increases of 1% and 6% respectively which indicates she is essentially performing an additional turn for little gain in hammer speed. This type of assessment shows how simply looking at the trend of hammer speed and cable force can assist with determining performance characteristics of individuals and quickly assessing where an athlete can improve.

While relationship between cable force and hammer speed is of high importance, the effects other variables have on hammer speed also need to be considered as it may be more effective or simpler to alter them in order to increase hammer speed. The tangential force contributes directly to hammer speed and for this reason it is important to have a strong understanding of the relationships between the cable force and its tangential component, and the tangential force and hammer speed. The strength of the relationship between the size of decreases in normalised cable force and normalised tangential force that was observed in the study alone suggests that a smaller decrease in cable force would lead to a reduction in the size of the decreases in tangential force however it may not be that straightforward.

The periods of negative tangential force coincided with decreasing hammer speed (Figures 2 and 4) and ideally the athlete should ensure that the effect of these negative periods of tangential force are minimised throughout the throw. It may not be possible for the thrower to entirely remove the periods of negative tangential force however; reducing the affect these periods have on losses in hammer speed is desirable. There are two ways that it may be feasible for the thrower to minimise the effect of negative tangential force: the first being by reducing the length that these periods occur for and the second by reducing the magnitude of the tangential force itself.

Analysis of the correlations determined in this study indicate that this cohort of throwers, and most probably other throwers of a similar level, could theoretically reduce the effect of negative tangential force by reducing its magnitude rather than by reducing the amount of time that this negative force is applied for. It is unknown whether this would also transfer to throwers who have a higher performance level. However, it must also be considered that reducing its

magnitude when negative could have an effect on what occurs when the tangential force is positive which is when the athlete should ensure this force is as large as possible. Although, inspection of Figure 4 indicates that as the throw progresses the magnitude of the tangential force, when negative in polarity, increases in size while the magnitude of the tangential force at its maximum remains approximately the same, for most participants, regardless of turn number (before the final turn) or the magnitude of the preceding minimum in tangential force. This could indicate that for the majority of these athletes the magnitude of the tangential force at its most negative has little effect on the magnitude of the proceeding positive maxima. This is in contrast to the data presented by Bartonietz (1994) for Yuriy Sedykh, who although also showed an increasingly negative tangential force component, displayed a greater increasing positive component as the throw progressed. This possibly reflects the greater skill level of Yuriy Sedykh compared to the throwers in the current study. Future investigation into this concept needs to occur to determine if it is physically possible for an athlete to reduce the negative tangential component while enhancing the positive component.

The magnitude of tangential force can be altered by either changing the magnitude of cable force itself or by changing the angle between the hammer velocity and cable force vectors (equation 2). Reducing the magnitude of cable force could be counterproductive when the thrower returns to double support and cable force leads the radius of rotation again as additional work would be required to increase the cable force to the level it would have been without a reduction. Additionally for a reduction in cable force to occur during single support the thrower would need to increase the magnitude of the radius which could be difficult given that they are already in an unstable position during single support. In this study the magnitude of the angle between the cable force and velocity at its maximum in each turn (when tangential force at its most negative) and the corresponding loss in hammer speed were found to be very strongly related which theoretically means that a smaller angle would lead to a smaller loss in hammer speed. The relationship between the magnitude of normalised cable force at the point in time when the angle between the cable force and velocity is at its maximum within each turn and the corresponding loss in hammer speed was also investigated and a moderate relationship was found between the two. These findings suggest that the angle at which the cable force vector is acting at relative to the hammer velocity has a greater effect on losses in hammer speed than the actual magnitude of the cable force which means it is more beneficial for athletes to make changes to technique that reduce the magnitude of this angle rather than the magnitude of the cable force during single support.

Conclusion

Analyses of the traces of tangential force showed, in agreement with the laws of physics, that decreases in hammer speed occur when the tangential force was negative and similarly, increases occurred when it was positive. The correlation analyses that were carried out in this study suggest that the most effective way to minimise the impact of negative tangential force is to reduce angle by which the cable force lags behind the radius of rotation as opposed to reducing the

amount of time spent applying negative tangential force. Further investigation into how an athlete would do this and whether this is a feasible option given the range of variation of the angle needs to be carried out by investigating the kinematics and kinetics of the thrower.

Future focus now needs to address the hammer throw technique to identify aspects of an athlete's kinematics that affect the hammer speed and the angle between the cable force vector and the instantaneous direction of the radius of rotation.

References

- Bartonietz, K. (1994). A biomechanical analysis of throws with different weight and length hammers. *Modern Athlete & Coach*, 32(4), 33-36.
- Bartonietz, K. (2000). Hammer throwing: Problems and prospects. In V. M. Zatsiorsky (Ed.), *Biomechanics in Sport: Performance Enhancement and Injury Prevention, volume 4* (pp. 458-486) Oxford: Blackwell Science Ltd.
- Bartonietz, K., Barclay, L., & Gathercole, D. (1997). Characteristics of top performances in the women's hammer throw: Basics and technique of the world's best athletes. *New Studies in Athletics*, 12(2), 101-109.
- Bartonietz, K., Hinz, L., Lorenz, G., & Lunau, G. (1988). The hammer: The view of the DVfL of the GDR on talent selection, technique and training of throwers from beginner to top level athlete. *New Studies in Athletics*, 3(1), 39-56.
- Brice, S. M., Ness, K. F., Rosemond, D., Lyons, K., & Davis, M. (2008). Development and validation of a method to directly measure the cable force during the hammer throw. *Sports Biomechanics*, 7, 274-287.
- Dapena, J. (1984). The pattern of hammer speed during hammer throw. and influences of gravity on its fluctuations. *Journal of Biomechanics*, 17, 553-559.
- Dapena, J., & Feltner, M. E. (1989). Influence of the direction of the cable force and of the radius of the hammer path on speed fluctuations during hammer throwing. *Journal of Biomechanics*, 22, 565-575.
- Dapena, J. (1985) Factors affecting the fluctuations of hammer speed in a throw. In D. A. Winter, R. W. Norman, R. P. Wells, K. C. Hayes and A. E. Palta (Eds.), *Biomechanics IX* (pp. 499-503). Illinois: Human Kinetics.
- Hopkins, W. G. (2006). A New View of Statistics: A Scale of Magnitudes for Effect Statistics. Retrieved May 4, 2010 from Internet Society for Sport Science: <http://www.sportsci.org/resource/stats/>.
- Hwang, I., & Adrian, M. (1984). Biomechanical analysis of hammer throwing. in Adrian, M., & Deutsch, H. (Eds), *Proceedings of the 1984 Olympic Scientific Congress* (pp. 79-86). Eugene: Oregon Microform Publications.
- IAAF. (2009). IAAF Competition Rules 2009. Retrieved August 20, 2009, from www.iaaf.org/competitions/technical/regulations/index.html
- Jabs, R.-G. (1979). Velocity in Hammer Throwing. *Track Technique*, 77, 2449-2450.
- Maheras, A. V. (2009). Reassessing velocity generation in hammer throwing. *New Studies in Athletics*, 24(4), 71-80.

- Murofushi, K., Sakurai, S., Umegaki, K., & Kobayashi, K. (2005). Development of a system to measure radius of curvature and speed of hammer head during turns in hammer throw. *International Journal of Sport and Health Science*, 3, 116-128.
- Murofushi, K., Sakurai, S., Umegaki, K., & Takamatsu, J. (2007). Hammer acceleration due to thrower and hammer movement patterns. *Sports Biomechanics*, 6, 301-314.
- Ohta, K., Umegaki, K., Murofushi, K., & Luo, Z. (2010) Analysis of hammer movement based on a parametrically excited pendulum model. *Procedia Engineering* 2.
- Susanka, P., Stepanek, J., Miskos, G., & Terauds, J. (1987). Hammer-athlete relationship during the hammer throw. in Terauds, J., Gowitzke, B. G., & Holt, L. E (Eds.), *Proceedings of oral sessions, IV International symposium of biomechanics in sports* (pp. 194-200). Del Mar: Academic Publishers.
- Tutevich, V. N. (1969). *Teorija sportivnych metanij*. [Theory of the throwing events]. Moscow: Fizkultura i Sport.
- Winter, D. A. (2005). *Biomechanics and motor control of human movement* (3rd edn.). Hoboken: John Wiley & Sons, Inc.

Appendix C: Publication of Chapter 5

This Appendix contains the manuscript of the paper relating to Chapter 5 of this thesis. This paper is currently under review.

Title: An analysis of the thorax-pelvis separation angle and its effect on hammer kinetics and kinematics in the hammer throw.

Keywords: hammer, kinematics, kinetics, thorax.

Author list: Sara M. Brice^{1,2}, Kevin F. Ness¹, Yvette L. Everingham¹ & Doug Rosemond²

¹School of Engineering and Physical Sciences, James Cook University

²Australian Institute of Sport Movement Science – Biomechanics

Acknowledgement:

The authors wish to thank staff of the Biomechanics and Performance Analysis Disciplines of the Australian Institute of Sport Movement Science Department for their assistance with the data collection for this study.

Abstract

This study investigated the relationship between thorax motion and key hammer kinetic and kinematic variables. Hammer positional data and rotation of the thorax relative to the pelvis (thorax-pelvis separation angle) were measured for ten throws of five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) throwers. Linear hammer speed, tangential component of the cable force and the angle between the cable force and hammer linear velocity vectors were calculated via hammer positional data. Thorax-pelvis separation was found to increase during single support and decrease during double support. It was also found that both the magnitude of the tangential force at its most negative and the loss in speed were smaller when the separation angle was decreased in the preceding double support phase, specifically in turn two and the second last turn. These findings suggest that throwers can reduce the size of losses in speed by reducing the size of the thorax-pelvis separation during double support.

Introduction

The hammer throw is one of the four track and field throwing disciplines and as with the other three, the aim is to project the hammer the greatest distance. Once a hammer has been released by a thrower it undergoes projectile motion and for this reason it is vital that a thrower ensures the speed of hammer at release is as high as possible. A thrower accelerates the hammer to its release by applying force to the hammer via the hammer's cable (cable force). Previous studies have found that the linear speed of the hammer fluctuates throughout the throw primarily as a result of the tangential component of the cable force

(tangential force) fluctuating between being positive and negative (Brice, Ness, & Rosemond, 2011; Dapena, 1984).

Much of the past literature suggests that the hammer can only be accelerated in the double support phase (Bartonietz, Barclay, & Gathercole, 1997; Bartonietz, 2000) and it is not possible for the thrower to actively influence the velocity in the single support phase (Rojas-Ruiz & Gutiérrez-Dávila, 2009). However, it has been suggested that throwers could in fact increase the speed of the hammer during the single support phase by increasing the vertical velocity of the hammer (Maheras, 2009). The majority of literature focuses on how throwers can actively increase the speed of the hammer within each turn, specifically during the double support phase with little focus being put towards how throwers could reduce the size of losses in speed in the subsequent single support phase. Ideally the losses in hammer speed that occur in the single support phase should be minimised (Brice et al., 2011; Morley, 2003).

Brice et al. (2011) investigated the relationship between the size of losses in speed and the time spent applying negative tangential force. They also considered the relationship between the size of losses in speed and the magnitude of the tangential force at its most negative. They found that it was the magnitude of the tangential force at its most negative rather than the amount of time spent applying negative force that had the greatest effect on losses in speed. Given this finding, Brice et al. (2011) hypothesized that a thrower may be able to reduce the size of losses in speed if they can reduce the magnitude of the tangential force when it is negative.

The magnitude of the tangential force (F_{Ct}) can be determined via,

$$F_{Ct} = |F_c| \cos \beta \quad (1)$$

where F_c is the cable force and β is the angle between the cable force and the hammer's linear velocity vectors (Brice et al., 2011). The terms in equation (1) indicate that a thrower can reduce the magnitude of the tangential force in two ways: by reducing the magnitude of the cable force or by reducing the angle between the force and velocity vectors. Brice et al. (2011) found that it was the angle, at its greatest, rather than the magnitude of the cable force that caused the size of the losses in speed to be either reduced or increased. These findings suggest that a thrower is best able to reduce the size of losses in speed, caused by the tangential force being negative, by reducing the magnitude of the angle in equation (1). While this study gave good insight into the relationship between the tangential force and speed it did not investigate the relationship between thrower kinematics and tangential force.

Hammer throw technique is strongly influenced by movement of the trunk (Otto, 1991, Morley, 2003). It is widely accepted that the angle between the shoulders and pelvis (shoulder-pelvis separation angle) increases during single support and decreases during double support as the thrower accelerates the hammer (Morris & Bartlett, 1995; Otto, 1991). While movement of the trunk or shoulders relative to the pelvis has been discussed in coaching literature it has received little research attention (Judge, Hunter, & Gilreath, 2008). Previous studies have investigated the relationship between performance outcomes and the

magnitude of the thorax-pelvis separation angle in a number of other sports that utilise thorax rotations such as discus and golf.

Like the hammer throw, the speed of the discus at release is the most important determinant of range (Bartlett, 1992) and the relationship between discus velocity and thorax-pelvis separation has been investigated in a number of studies (Leigh & Yu, 2007; Leigh, Gross, Li, & Yu, 2008). Leigh, Gross, Li and Yu (2008) analysed the techniques of 51 male and 53 female skilled throwers and found that throwers should maintain their hip-shoulder and shoulder-arm separation angles during the throw as this allows the discus to travel over a longer path and results in the horizontal component of the release velocity being larger.

In golf studies the thorax-pelvis separation angle is referred to as the X-factor and is typically determined by computing the difference between the thorax and pelvis axial rotation angles projected onto the horizontal plane (Chu, Sell, & Lephart, 2010; Horan, Evans, Morris, & Kavanagh, 2010; Myers et. al., 2008). The relationship between X-factor and golf performance has been researched extensively. A number of studies have reported positive relationships between X-factor and clubhead velocity which indicates that athletes could increase ball velocity by increasing the X-factor during the golf swing (Chu, Sell, & Lephart, 2010; Myers et. al., 2008). More recent work has tested the validity of methods used to calculate the X-factor and there was no mechanically meaningful relationship found to exist between X-factor and the maximum clubhead velocity (Kwon, Han, Como, Lee, & Singhal, 2013).

The purpose of this present study was to investigate thorax-pelvis separation in the hammer throw and its relationship with key hammer kinetic and kinematic variables. Previous work has focused on how hammer throwers could reduce the size of the losses in speed that occur within each turn (Brice et al., 2011). In this present study the relationship between thorax-pelvis separation and the size of losses in speed, the magnitude of the tangential force at its most negative and the maximum size of the angle between the cable force and velocity vectors when the tangential force is negative were investigated. It was hoped the findings of this investigative study would give athletes and coaches a clear indication as to how to reduce the size of losses in the hammer speed, by making changes to the magnitude of the thorax-pelvis separation angle at key times in the throw.

Methods

Five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) hammer throwers participated in this study. Each participant was in the competition phase of the Australian athletics domestic season and was competing at the open national level. All participants gave written informed consent to participate in this study which was given ethical approval by the James Cook University Human Ethics Committee and the Australian Institute of Sport Ethics Committee.

Participants were asked to complete ten throws with a competition standard hammer (7.26 kg for males and 4 kg for females) that had retro-reflective markers positioned on the hammer's cable at known distances from the centre of the hammer's head. In addition retro-reflective markers (15 mm in diameter) were positioned on anatomical landmarks in accordance with the Vicon Plug-in Gait marker placement protocol (Davis, Öunpuu, Tyburski, & Gage, 1991). The markers that were used to model the thorax were positioned on the sternoclavicular notch, xiphoid process, spinous process of the C7 vertebra and the spinous process of the T10 vertebra. The markers that were used to model the pelvis were positioned on the left and right anterior superior iliac spine and the left and right posterior superior iliac spine. Prior to data collection each participant was allowed to complete their usual warm up procedures.

A 21 infra-red camera system (Oxford Metrics, Oxford, UK) sampling at a frame rate of 250 Hz was used to record all three dimensional marker coordinate data. Testing was performed at an outdoor athletics facility after twilight conditions due to the use of the infra-red cameras. The recorded video footage was post processed in Vicon Nexus (Oxford Metrics, Oxford UK) using the same data processing and filtering protocols outlined by Brice et al. (2011).

The hammer marker positional data were used along with direction cosines to determine the position of the hammer's head from entry through to release where entry and release were defined in the same way as Brice et al. (2011). The hammer head positional data were then used to determine linear hammer speed, the cable force and its tangential component (Brice et al., 2011). Cable force was determined using the following equation,

$$\mathbf{F}_c = m \left(\frac{d^2 \mathbf{s}}{dt^2} - \mathbf{g} \right) \quad (2)$$

Where m is the mass of the hammer (7.26 kg for males; 4 kg for females), \mathbf{s} is the three dimensional position of the hammer's head at any time t and \mathbf{g} is the gravity vector (Brice et al., 2011). The tangential component of the cable force was determined using equation (1), outlined in the introduction. All force data were normalised for hammer weight to account for the difference between the hammers used by the two genders.

The filtered body marker data were used to create rigid models of the thorax and pelvis via the Plug-in Gait modelling functions in Vicon Nexus. The angle between the sagittal axes (or frontal planes) of the thorax and pelvis segments (thorax-pelvis separation angle) was output from Vicon Nexus. In this study thorax-pelvis separation angle was positive when the thorax leads the pelvis and negative when the pelvis leads thorax (Figure 1). Traces of the thorax-pelvis separation angle were produced to build an understanding of how a thrower moves their thorax relative to their pelvis as these data have not been specifically reported in the literature.

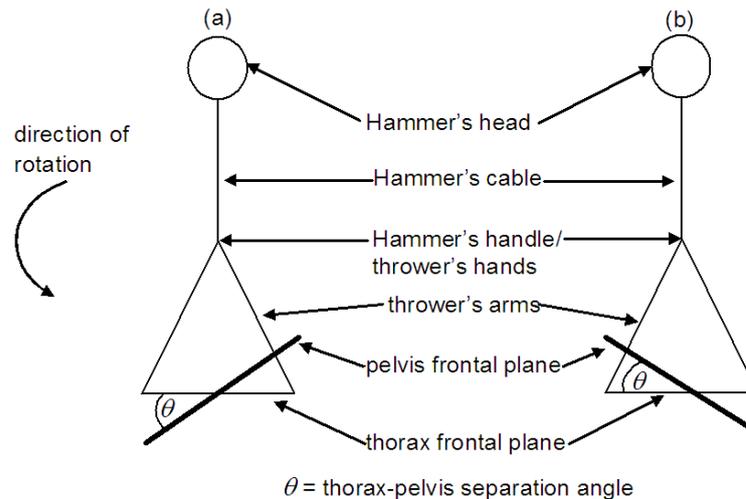


Figure 1. Overhead view of the thorax-pelvis separation angle. Angle is defined as being (a) negative (pelvis leading thorax) and (b) positive (thorax leading pelvis) for a right-handed thrower.

For each turn, the loss in speed, tangential force at its most negative and the angle between the linear velocity and cable force vectors at its greatest (maximum lag angle) were determined. These values were then averaged over the ten throws so that each participant had a mean value for each turn of the above mentioned variables. The thorax-pelvis separation angle at its smallest within each turn was also determined.

The relationships between the separation angle at its smallest, and the above mentioned hammer kinetic and kinematic variables were examined. Pearson's correlation and the associated p-values (p) measured the strength of these relationships. A relationship was deemed to be significant if $p < 0.05$. All correlations were classified using the definitions described by Hopkins (2006). Scatterplots of the bivariate relationships between each of the correlates were also explored for the effects of outlying observations and a cluster analysis was also performed in IBM SPSS statistics (IBM Corporation, New York US) to confirm the existence of any outliers.

Three different turning methods were utilised by the participants of this study: three turn ($n = 2$), four turn ($n = 7$) and five turn ($n = 1$). For each of the correlation analyses the turns were classified as turn one, turn two, second last turn and final turn. Table 1 shows which turn number of the three different turning methods was included in each of the four aforementioned analysis classifications. For three turn throwers turn two data were used in both the second turn and second last turn correlation analyses, whilst the turn three data for the five turn thrower was not included in any of the correlation analyses.

Table 1: Turn number used in each of the correlation analyses of this study.

No. of turns	First turn analyses	2 nd turn analyses	2 nd last turn analyses	Final turn analyses
3	1	2	2	3
4	1	2	3	4
5	1	2	4	5

Results

The thorax-pelvis separation angle is predominantly negative throughout each throw (data for each participant's furthest throw displayed in Figures 2 and 3). For the majority of participants the size of the separation angle decreased during double support and increased during single support (Figures 2, 3a and 3b). The exceptions to this were three of the female participants whose data are displayed in Figures 3c, 3d and 3e. For all three of these females the angle decreased during double support and increased during single support in turn one and for two of them this trend was also observed in turn 2 (Figures 3c and 3e).

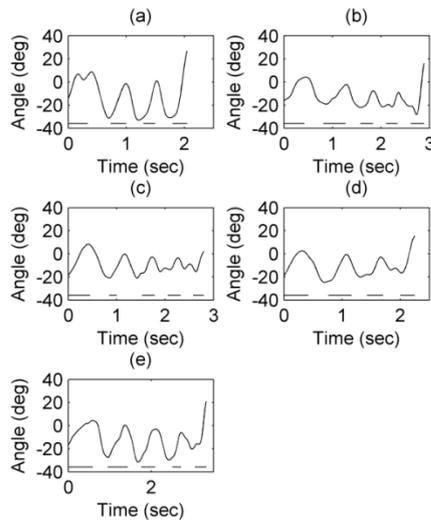


Figure 2. Traces of the thorax-pelvis separation angle for the furthest throw of male participants: (a) three turn thrower (63.22 m), (b) four turn thrower (61.45 m), (c) four turn thrower (60.71 m), (d) three turn thrower (57.69 m) and (e) four turn thrower (42.61 m). Note: black lines at the bottom of each graph indicate when the athlete is in double support.

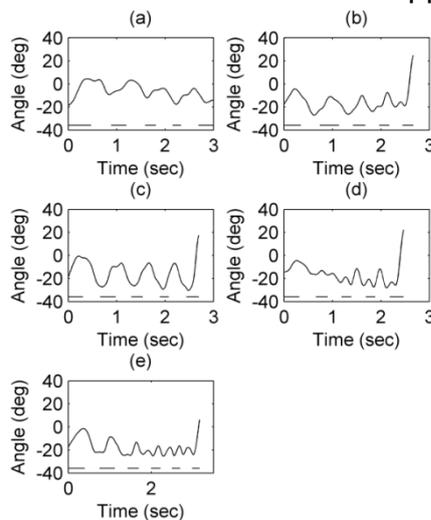


Figure 3. Traces of the thorax-pelvis separation angle for the furthest throw of female participants: (a) four turn thrower (59.86 m), (b) four turn thrower (57.59 m), (c) four turn thrower (55.66 m), (d) four turn thrower (54.54 m) and (e) five turn thrower (54.43 m). Note: black lines at the bottom of each graph indicate when the athlete is in double support.

For two of these three females (Figures 3c and 3e), the angle continued to follow the trend of decreasing during double support for their remaining turns. The pattern observed during their single support phases differed. For turns three and four of one of these females (Figure 3c), it was found that the angle began increase later in the single support phase than it did for the other participants. For the other, (Figure 3e) the angle had periods where it both increased and decreased during the single support phases of turns three, four and five. For the female participant whose data are displayed in Figure 3d, the angle was found to increase and decrease during both support phases for turns two, three and four.

Strong, positive correlations were found between normalised tangential force at its most negative (F_{\min} in Table 2), and the separation angle at its smallest in turn two ($R = 0.79$, $p < 0.05$) and the second last turn ($R = 0.71$, $p < 0.05$). No other correlates were found to be statistically significant. However, scatterplots displaying these bivariate relationships revealed that three participants produced consistently larger minimum separation angles than the other seven participants (indicated by the square markers in Figures 4, 5 and 6). Furthermore, these data points corresponded to the three lightest participants, who all happened to be female. These three points formed a cluster of their own following a hierarchical cluster analysis based on a squared Euclidean distance measure (Johnson & Wichern, 2007). Hence the correlation measures were recomputed with these three points removed (Table 2). The strength of the relationship between the minimum separation angle and the tangential force at its most negative subsequently increased (Table 2). Moreover, this relationship was also observed for turn one. While the turn one result is statistically significant, this was caused by an additional outlier affecting the correlation calculation (indicated by the circle in Figures 4, 5 and 6). Evidence generated from a cluster analysis supported this point to be distinctively different from the rest when it was found to be grouped in the same cluster as the other three outliers for turn one. When this additional data point was omitted from the correlation calculation, the relationship was no longer statistically significant for turn one (Table 2).

Table 2: Persons correlation coefficients for relationship between thorax-pelvis separation angle at its smallest within each turn and selected hammer kinetic and kinematic variables.

Variable	Turn one ^b		Turn one ^a		Turn two ^a		2 nd last turn ^a		Last turn ^a	
	R	p	R	p	R	p	R	p	R	p
F_{\min}	0.19 [#]	0.72	0.86	0.01	0.95*	0.00	0.78*	0.04	0.48	0.27
Speed loss	0.22 [#]	0.67	-0.77*	0.04	-0.97*	0.00	-0.81*	0.03	-0.51	0.20
Maximum lag angle	-0.49 [#]	0.32	-0.90	0.01	-0.88*	0.01	-0.87*	0.01	-0.71	0.08

Asterisks indicate statistical significance ($p < 0.05$); ^aThree females excluded from all these analyses; ^b Recomputed with an additional outlier excluded (Indicated by the circle marker in Figures 3(a), 4(a) and 5(a)).

A number of other strong, statistically significant relationships were found to exist when the three outliers were omitted from the correlate calculations in Table 2. A very strong, negative relationship was found between minimum separation angle and the subsequent loss in speed during the single support phase for turn one, turn two and the second last turn. There was also a strong,

negative relationship between minimum separation angle and the maximum lag angle between the cable force and linear velocity vectors. These relationships were significant for turn one, turn two and the second last turn. However, as was with the previous result for the tangential force, the first turn result was affected by an additional outlier (indicated by the circle marker in Figures 4, 5 and 6).

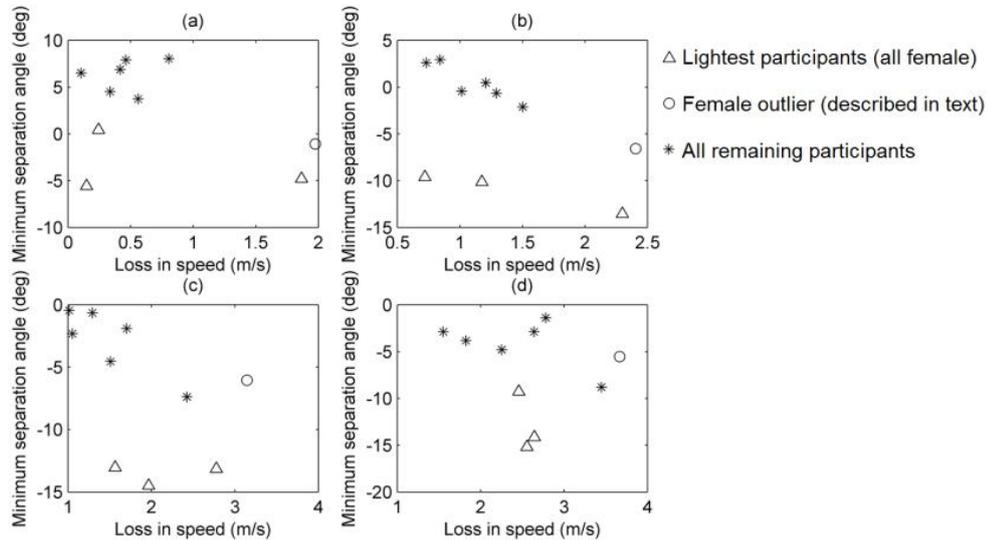


Figure 4. Scatterplots of data used to obtain correlations between minimum separation and normalised tangential force at its minimum in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

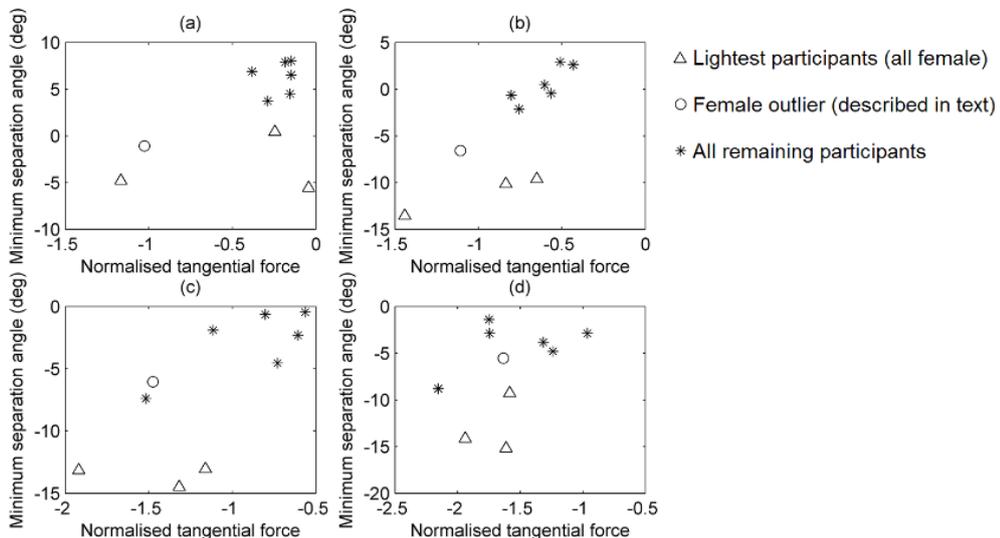


Figure 5. Scatterplots of data used to obtain correlations between minimum separation and the subsequent loss in speed in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

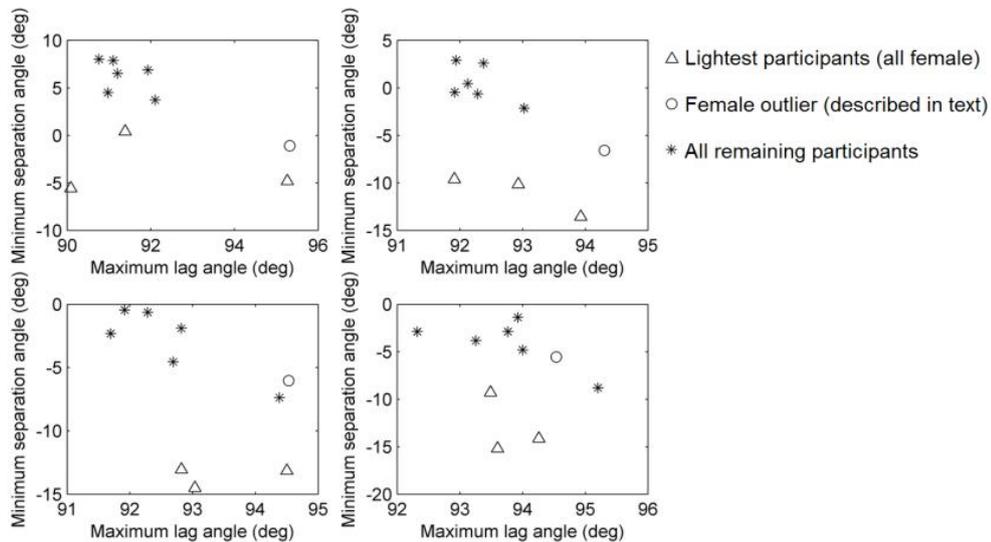


Figure 6. Scatterplots of data used to obtain correlations between minimum separation and maximum lag angle between the cable force and hammer linear velocity vectors at its maximum in: (a) turn 1, (b) second turn, (c) second last turn and (d) last turn.

Discussion and Implications

The purpose of this study was to investigate the thorax-pelvis separation in the hammer throw. The trends of the traces of thorax-pelvis separation angle in Figures 2 and 3 show that the angle is predominantly negative which indicates that the pelvis is typically leading the thorax throughout the throw. The magnitude of this angle was also found to generally increase during single support (when hammer speed is decreased) and decrease during double support (when hammer speed is increased) which is consistent with what has been reported previously in the literature (Morriss & Bartlett, 1995; Otto, 1991). These traces also give an indication as to the size of the separation throughout the throw which has not been reported previously in the literature.

For the participants whose data are displayed in figures 3d and 3e there are small oscillations present in the trough regions (e.g. between 1 and 1.5 seconds for the female subject in Figure 3d). It is unknown why these oscillations occur but, these two participants were the least skilled females of this cohort (best throws of 54.54 m and 54.43 m respectively). These two participants were also two of the three outliers excluded from the correlate calculations for the data reported in Table 2. This could indicate some technique flaw or strength issue resulting in these participants not being in complete control of the hammer.

The strength of the relationships reported in Table 2 indicates that hammer speed losses during single support are smaller when the thrower is able to reduce the angle between the frontal planes of the thorax and pelvis during the preceding double support phase, particularly in the second and second last turns of the throw. This is in agreement with coaching literature that suggests that the thorax-pelvis separation should be approximately zero when the hammer is at its lowest point (Morley, 2003).

While it is accepted that the losses in speed that occur during single support can't be eliminated (Brice et al., 2011), throwers should ensure that the magnitude of these losses are kept to a minimum (Brice et al., 2011; Morley, 2003) as once they return to double support they first need to account for these losses before they can continue to build the hammer's linear speed. This leads to the suggestion that throwers of this cohort, and those of similar ability, should aim to reduce the thorax-pelvis separation angle by as much as possible during the double support phase by focusing on rotating the thorax in the direction of the throw. This would be rotation in the anticlockwise direction for a right-handed (Figure 2) thrower and clockwise for a left-handed thrower. Currently, it is unknown if it is possible for a thrower to manipulate the thorax-pelvis separation during the throw. However, the period of double support is when the athlete is at their most stable and Figures 2 and 3 indicate that generally the angle is already being decreased by the participants during double support so it is most probably the period of time when it is easiest for an athlete to manipulate the separation angle.

Reducing the thorax-pelvis separation during double support also appears to result in a smaller maximum lag angle between the cable force and velocity vectors and smaller magnitude for the normalised tangential force at its most negative in the subsequent single support phase (Table 2). Brice et al. (2011) previously found that this lag angle at its greatest has the greatest influence on the size of losses in speed within each turn hence any reduction in the size of this lag angle will likely lead to smaller losses in linear hammer speed.

One limitation of this study that needs to be considered is the utilisation of the Pearson's correlation coefficient as extreme cases (outliers) can result in correlates that are misleading (Asuero, Sayago, & González, 2006). In this present study, scatterplots were produced and cluster analyses were performed to determine the existence of outliers in the data sets. Where outliers were found to exist, the correlates were recomputed with outliers removed. Another limitation of Pearson's correlation is it assumes the relationship between the two variables is linear. The exploratory data analyses that were performed in this study suggested this assumption was reasonably met. Another assumption of the correlation analysis is that which deals with homoscedasticity; where the variability for one variable is similar to the variability of the other variable. The initial investigations, where all subject's data were included, violated this assumption and hence these results should be interpreted with care. This issue was resolved by working with a more homogenous subset of data that excluded participants from the more variable cluster.

Another limitation of this study is the throwing ability of the participants. The current world record distances in the hammer throw are 86.74 m and 79.42 m for men and women respectively (<http://www.IAAF.org>). In this study the average distance thrown was 54.3 ± 7.6 m for the male participants and 53.9 ± 3.2 m for the female participants which are considerably lower than the distances thrown by the world's leading athletes. Therefore any of the findings found of this study can only be applied to this cohort or throwers of similar ability. Further investigation needs to be carried out to ascertain whether the relationships observed here hold true for more skilled throwers.

Conclusion

The relationship between thorax-pelvis separation angle and key kinematic and kinetic variables of the hammer were analysed in this study. Separation angle was chosen for analysis as it was thought that with training an athlete could manipulate this variable, particularly during double support. The results of this study indicate that this cohort of throwers (and throwers of similar ability) should aim to reduce the thorax-pelvis separation angle during double support by as much as possible, specifically during turn two and the second last turn. This results in a smaller loss in speed during the subsequent single support phase.

Future work should be done to assess if the relationships observed here are present for more highly skilled hammer throwers. In addition to this, an intervention study should be undertaken to assess if an athlete can adjust their technique by making the changes outlined here and assess how such changes may lead to enhanced performance.

References

- Asuero, A. G., Sayago, A., & González, A. G. (2006). The correlation coefficient: An overview. *Reviews in Analytical Chemistry*, 36, 41-58. doi:10.1080/10408340500526766
- Bartlett, M. (1992). The biomechanics of the discus throw: A review. *Journal of Sports Sciences*, 10, 467-510. doi:10.1080/02640419208729944
- Bartonietz, K. (2000). Hammer throwing: Problems and prospects. In V. M. Zatsiorsky (Ed.), *Biomechanics in Sport: Performance Enhancement and Injury Prevention, Volume 4* (pp. 458-486) Oxford: Blackwell Science Ltd.
- Bartonietz, K., Barclay, L., & Gathercole, D. (1997). Characteristics of top performances in the women's hammer throw: Basics and technique of the world's best athletes. *New Studies in Athletics*, 12(2), 101-109. Retrieved from <http://194.213.2.7/wps/portal/iaaf>
- Brice, S. M., Ness, K. F., & Rosemond, D. (2011). An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers. *Sports Biomechanics*, 10, 174-184. doi:10.1080/14763141.2011.592210
- Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences*, 28, 1251-1259. doi:10.1080/02640414.2010.507249
- Dapena, J. (1984). The pattern of hammer speed during a hammer throw and the Influence of gravity on its fluctuations. A three-dimensional analysis of angular momentum in the hammer throw. *Journal of Biomechanics*, 17, 553-559. doi:10.1016/0021-9290(84)90086-1
- Davis III, R. B., Öunpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science*, 10, 575-587. doi: 10.1016/0167-9457(91)90046-z
- Horan, S. A., Evans, K., Morris, N. R., & Kavanagh, J. J. (2010) Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *Journal of Biomechanics*, 43, 1456-1462. doi:10.1016/j.jbiomech.2010.02.005

- Hopkins, W. G. (2006). A scale of magnitudes for effect statistics. *A new view of statistics*. Retrieved from <http://sportsci.org/resource/stats/effectmag.html>
- Johnson, R. A., & Wichern, D. W. *Applied multivariate statistical analysis*. Upper Saddle River: Prentice Hall.
- Judge, L. W., Hunter, I., & Gilreath, E. (2008). Using sport science to improve coaching: A case study of the American record holder in the women's hammer throw. *International Journal of Sports Science & Coaching*, 3, 477-488. doi:10.1260/174795408787186440
- Kwon, Y.-H., Han, K. H., Como, C., Lee, S., & Singhal, K. (2013) Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers. *Sports Biomechanics*. doi:10.1080/14763141.2013.771896
- Leigh, S., Gross, M. T., Li, L., & Yu, B. (2008). The relationship between discus throwing performance and combination of selected technical parameters. *Sports Biomechanics*, 7, 173-193. doi:10.1080/14763140701841399
- Leigh, S., & Yu, B. (2007). The association of selected technical parameters with discus throwing performance: A cross-sectional study. *Sport Biomechanics*, 6, 269-284. doi:10.1080/14763140701489744
- Morley, M. (2003). Hammer throwing: The turns – part 1. *The Coach*, 16(May/June), 21-25.
- Maheras, A. V. (2009), Reassessing velocity generation in hammer throwing. *New Studies in Athletics*, 24(4), 71-80, viewed 15 March 2011. Retrieved from <http://194.213.2.7/wps/portal/iaaf>
- Morriss, C. J., & Bartlett, R. M. (1995). Biomechanical analysis of the women's hammer throw. In R. M. Bartlett (Ed.), *Biomechanical Analysis of the 1995 National Championships* Vol. 1 (1-20). Alsager: British Athletic Federation.
- Myers, J., Lephart, S., Tsai, Y.-S., Sell, T., Smoliga, J., & Jolly, J. (2008) The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports Sciences*, 26, 181-188. doi:10.1080/02640410701373543
- Otto, R. M. (1991). A kinematic analysis of Yuriy Sedikh's world record hammer throw. *Modern Athlete and Coach*, 29(4), 3-5.
- Rojas-Ruiz, F. J., & Gutiérrez-Dávila, M. (2009) The relation between angular displacement of the hammer in the double support phase and its velocity in the hammer throw. *Journal of Human Sport and Exercise*, 4, 254-261. doi:10.4100/jhse.2009.43.07

Appendix D: Publication of Chapter 6

This Appendix contains the manuscript of the paper relating to Chapter 6 of this thesis. This paper has been accepted for publication in *Journal of Sport and Health Sciences*. The paper is currently in press.

Title: Validation of a method to predict hammer speed from cable force

Keywords: Athletics; Force; Hammer; Measurement; Speed; Throwing

Author list: Sara M. Brice^{1,2}, Kevin F. Ness¹ & Doug Rosemond²

¹School of Engineering and Physical Sciences, James Cook University

²Australian Institute of Sport Movement Science – Biomechanics

Acknowledgement

The authors wish to thank Mr Mark Davis for the technical development and support with this study and the staff of the Biomechanics Stream of the Australian Institute of Sport Movement Sciences Discipline for their assistance with the data collection for this study.

Abstract

Purpose:

The purpose of this study was to develop and validate a method that would facilitate immediate feedback on linear hammer speed during training.

Methods:

Three-dimensional hammer head positional data were measured and used to calculate linear speed (calculated speed) and cable force. These data were used to develop two linear regression models (shifted and non-shifted) that would allow prediction of hammer speed from measured cable force data (predicted speed). The accuracy of the two models was assessed by comparing the predicted and calculated speeds. Averages of the coefficient of multiple correlation (CMC) and the root mean square (RMS) of the difference between the predicted and calculated speeds for each throw of each participant were used to assess the level of accuracy of the predicted speeds.

Results:

Both regression models had high CMC values (0.96 and 0.97) and relatively low RMS values (1.27 m/s and 1.05 m/s) for the non-shifted and shifted models, respectively. In addition, the average percentage differences between the predicted and calculated speeds were 6.6% and 4.7% for the non-shifted and shifted models, respectively. The RMS differences between release speeds attained via the two regression models and those attained via three-dimensional positional data were also computed. The RMS differences between the predicted and calculated release speeds were 0.69 m/s and 0.46 m/s for the non-shifted and shifted models, respectively.

Conclusion:

This study successfully derived and validated a method that allows prediction of linear hammer speed from directly measured cable force data. Two linear regression models were developed and it was found that either model would be capable of predicting accurate speeds. However, data predicted using the shifted regression model were more accurate.

1. Introduction

In the hammer throw, the hammer undergoes projectile motion once it is released by the thrower. For this reason it is crucial for throw performance that the speed of the hammer at the instant of release is as large as possible. The athlete accelerates the hammer to its release speed by performing turns across the throwing circle during which time the hammer is subjected to a force exerted by the athlete through the cable (cable force).¹ A single fluctuation in the linear hammer speed occurs within each turn and the magnitudes of these fluctuations vary between athletes.²

Brice et al.³ observed a strong relationship ($r = 0.87$) between the size of these fluctuations and the maximum angle the cable force acts at, relative to the linear velocity, in each turn. These findings suggest that during single support, a thrower could reduce the size of speed losses if they decrease the size of this angle. By reducing the size of the losses in speed the overall speed development will be enhanced which is crucial to throw success given the relationship that exists between release speed of the hammer and throw performance. Throughout a throw, the variation in the angle between the cable force and linear velocity is not large³ and it may be difficult for an athlete and/or coach to assess how technique alterations are affecting this angle. The only accurate way to assess whether an athlete is reducing the maximum size of this angle is to directly measure the angle or monitor the associated losses in hammer speed.

Currently angle and linear speed can only be accurately determined from hammer head positional data. Automatic tracking is the quickest method that could be used to collect this positional data. However, this is time consuming, post-processing is required and immediate feedback in the training environment is not possible via this method. For an athlete to be able to improve technique it is vital to have accurate information about their performance and any delay in providing the information reduces the likelihood that the athlete will be able to make effective use of the feedback.⁴ Therefore, it would be highly beneficial if there were a method that allowed accurate feedback in the training environment on the behaviour of the linear hammer speed. This would allow an athlete and coach to ascertain if technique alterations are beneficial or detrimental.

It is also possible to attain accurate linear hammer speed data via utilisation of its relationship with the instantaneous radius of curvature and the centripetal force. The relationship that exists between centripetal force (F), linear velocity (v) and instantaneous radius of curvature (r) is given by,

$$F = \frac{mv^2}{r} \quad (1)$$

where m is the mass of the hammer. The mass term in the above equation is the only constant. Therefore, in order to attain accurate linear speed data via the above equation, both the centripetal force and radius of curvature would need to be directly measured throughout the throw.

Murofushi et al.⁵ have previously presented a method that uses the above relationship along with the relationship between linear and angular velocity to determine linear hammer speed and radius of curvature during the throw. This measuring system added a total mass of 0.37 kg to the hammer and consisted of two strain gauges, that measured the cable force (not centripetal force), and two single axis accelerometers that were used to determine the angular velocity. There was good agreement between the measured linear speed and the speed calculated from hammer head positional data. However, there was an obvious phase lag between the two data sets. It was hoped that in this current study a more accurate method could be developed to determine hammer speed that would eliminate the phase lag observed in the data set of Murofushi et al.⁵ In addition, it was hoped that a measuring device that added negligible mass to the hammer system could also be utilized.

Brice et al.⁶ have previously reported an alternate method to directly measure cable force magnitude in the training environment. This system added negligible mass to the hammer system and consisted of a single strain gauge mounted directly on the hammer's cable. An average error 3.8% for a force of 2000 N when compared with cable force derived from hammer head positional data was reported. It is important to note that the cable force itself is not equal to the centripetal force. The cable force consists of three components: normal, radial, and tangential to the instantaneous circle of rotation.^{2,7} The radial component is considerably larger than the other two components and it is nearly equal to the centripetal force acting on the hammer. Due the complex motion of the hammer during the turns it is not possible to derive a simple, usable expression relating the hammer speed to the cable force. However since the cable force is by far the largest contributor to the centripetal force in equation (1), it was thought that the measurement system described above could be used in conjunction with a regression model to predict speed squared from cable force.

The purpose of this study was to investigate whether the relationship between the cable force and squared linear hammer speed could be used to develop a model that would allow speed to be predicted from measured cable force in the training environment. This type of information could be utilized by the athlete and coach to assess if changes in technique are reducing or increasing the losses in speed that occur within each turn.

2. Materials and methods

Five male (height: 1.88 ± 0.06 m; body mass: 106.23 ± 4.83 kg) and five female (height: 1.69 ± 0.05 m; body mass: 101.60 ± 20.92 kg) hammer throwers participated in this study. Each participant was in the competition phase of the Australian athletics domestic season and was competing at the open national level. Prior to data collection, all participants gave written informed consent to participate in this study which was given ethical approval by the James Cook University Human Ethics Committee and the Australian Institute of Sport Ethics Committee.

Participants were required to perform 10 throws with hammers instrumented with a strain gauge device (sampling at 500 Hz), previously described by Brice et al.⁶ This device measured the cable force throughout each throw (measured force). Retro-reflective markers were positioned on the hammer's cable at known distances from the centre of the hammer's head. A 21 infra-red camera system (Oxford Metrics, Oxford, UK) sampling at a frame rate of 250 Hz was used to collect the marker three-dimensional coordinate data. All video footage were post processed using the Vicon Nexus software suite (Oxford Metrics, Oxford, UK). All marker positional data were filtered using the same filter level reported by Brice et al.³ Positional data were then used in conjunction with direction cosines to determine the three-dimensional coordinate data for the centre of the hammer's head. These positional data were used to calculate hammer linear velocity (calculated speed) and cable force (calculated force).³ All calculated and measured force data were normalised for hammer weight to account for the fact that males use a heavier hammer than females.

Two regression models were developed that allowed speed to be predicted from measured force data (predicted speed). The calculated speed data and calculated force data were used to develop these regression models. All calculated speed data used in the regression model development were squared due to the mechanical relationship that exists between centripetal force and linear velocity squared (equation (1)).

The first regression model was derived from the square of the calculated speed and the calculated force (non-shifted regression). While the second model was derived from the square of the calculated speed and a time shifted calculated force (shifted regression). The shifted regression model was developed because earlier work showed a phase lag between speed and cable force³ and it was thought that accounting for the phase lag in the model development may lead to a model that would produce speed data that were more accurate. As the magnitude of this phase lag varies depending on turn number, throw, and athlete, it is not possible to apply the same time shift to every throw. It was therefore decided to time shift the calculated force such that for each throw the final peaks in the calculated force and calculated speed coincided. This time shift was applied to ascertain if removal of the phase lag resulted in a more accurate regression. As only the final peaks were aligned, there was no change in the frequency of the force data.

The calculated speed and calculated force data used to calculate the shifted regression were also trimmed as the final peak in the calculated force data occurred prior to release whereas the final peak in speed occurred at release. The calculated force data were trimmed so that the final peak was the final data point and the calculated speed data were trimmed by the same amount at the start. This was done so that both data sets were the same size.

A shifted and non-shifted regression equation was developed for each of the participant's 10 throws and all data points of each throw were used to develop these equations. The Matlab software suite (The Mathworks, Natick, MA, USA) was used to determine the regression equations and the y intercepts for both were also forced through (0,0) since equation (1) predicts zero speed for zero force. Averages of the gradients of the two linear regression equations were determined for the cohort.

The shifted and non-shifted regression models were then used to predict speed squared from measured force data and the square root of these squared speed data was taken to determine linear hammer speed (predicted speed). It was expected that the predicted speed data would closely agree with the magnitude of calculated speed for each trial. However, it was expected that the phase lag that exists between cable force and linear hammer velocity, previously described above, would still be evident in the predicted speed data resulting in peaks in the predicted speeds not coinciding with those in the calculated speeds.

The calculated force and measured force data are in phase; therefore the phase lag described above is also present between the calculated speed and the measured force. To reduce the effect of the phase lag, all measured force data were also time shifted and trimmed so that the final peak in the measured force coincided with release. As with the calculated force, the magnitude of the phase lag varies depending on turn number, throw, and athlete, so it is not possible to apply the same time shift to every throw. It was hoped that using measured force data that are time-shifted would result in predicted speed data that were more closely matched to both the magnitude and waveform of the calculated speeds than if the time shift were not applied.

The predicted speed data were then compared with the calculated speed data to ascertain the level of accuracy. The root mean square of the differences (RMS) was determined to compare the closeness in magnitude between the predicted and calculated speeds for each throw of each participant.⁸ These RMS values were then used to determine the average RMS values for the entire group. The average RMS difference between the calculated and predicted release speeds was also determined. The coefficient of multiple correlation (CMC) was determined to assess the closeness in the shapes between the predicted and calculated speed waveforms for each throw of each participant.^{8,9} The average CMC values was then determined for the entire group. A schematic of the process outlined here is shown in Fig. 1.

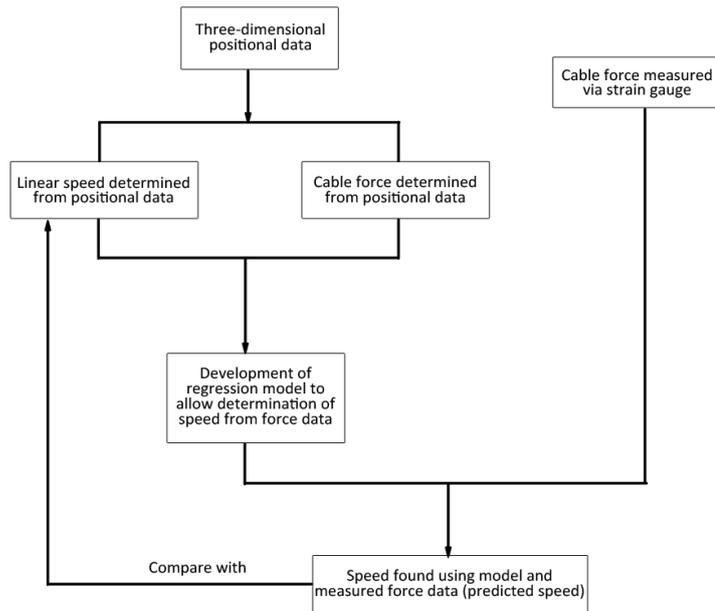


Fig. 1. Model of the data processing undertaken to validate predicted speed data.

3. Results

The regression equations, CMC and RMS values of the two models are similar (Table 1). Both models give high CMC values (0.96 and 0.97). In addition, the reported RMS values of 1.27 m/s and 1.05 m/s are relatively low for the non-shifted and shifted models, respectively. In addition, the average percentage difference between the calculated speeds and the speeds determined via the non-shifted and shifted models were 6.6% and 4.7%, respectively.

For the release speed, the RMS differences between the calculated and predicted values are 0.69 ± 0.49 m/s and 0.46 ± 0.34 m/s for the non-shifted and shifted models, respectively.

Table 1. Regression equations used to predict speed squared from normalized measured force data, the coefficient of multiple correlation (CMC) and the root mean square (RMS) of the difference between the calculated speed and the predicted speed (mean \pm SD).

	Gradient	y intercept	CMC	RMS (m/s)
Non-shifted	16.35 ± 0.48	0	0.96 ± 0.05	1.27 ± 0.65
Shifted	17.08 ± 0.59	0	0.97 ± 0.04	1.05 ± 0.59

4. Discussion

The magnitudes of the predicted speeds found using the two regression models were similar to the magnitudes of the calculated speeds as the RMS values were both low (Table 1). The shifted model gives both lower overall RMS difference in speeds and in particular lower RMS difference in release speed. The waveforms of the predicted speeds were also similar to the waveforms of the calculated speeds as the CMC values for both were close to one which

indicates similarity between the shapes of the waveforms⁹ (Table 1, Fig. 2). It is therefore feasible that either model could be used. However, the slightly lower RMS values of the shifted model indicates that the shifted model predicts speed data that are, on average, slightly more consistent. In addition, if athletes and coaches wish to quantify release speeds in the training environment they should utilize the shifted model as the predicted release speeds are more accurate than those found using the non-shifted model.

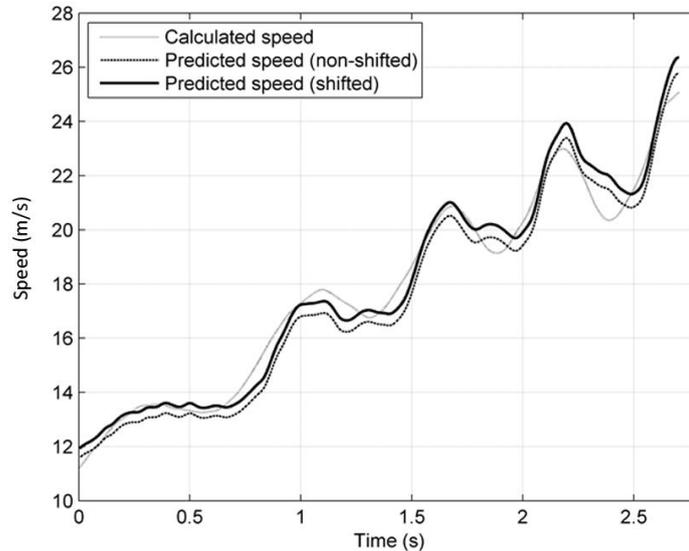


Fig. 2. Traces of calculated speed and predicted speeds from a single trial of a male participant.

The calculated speeds exhibit simple maxima and minima behavior (Fig. 2). Both the measured and calculated force data also exhibit simple maxima behavior. However, the behavior of the measured and calculated force data in the trough regions is more complicated.⁶ There are small fluctuations present in the trough regions that are consequently observed in the predicted speed data (Fig. 2). As a result, there is more error associated with the trough regions of the predicted speed data. This is a limitation that could potentially be an issue for athletes and coaches if they are quantifying the size of the fluctuations in the speed. In addition, there is also error resulting from use of the strain gauge device itself. The magnitude of this error has been previously reported in the literature.⁶

The regression model developed in this study is a model between velocity squared and cable force, based on equation (1). Implicit in this model are two assumptions and therefore sources of error. Firstly, the model assumes that the cable force is major contributor to the centripetal force throughout the throw. Secondly, the model assumes that the velocity is determined only by the cable force and therefore the effect of changes in the instantaneous radius of rotation on the velocity has been ignored. Both of these assumptions will degrade the goodness of the fit of the model. However, both assumptions have been validated given the strong correlations and relatively low RMS differences between the predicted and calculated velocities.

Time shifting the measured force data resulted in predicted speeds that had peaks and troughs that lined up closely with the peaks and troughs in the

calculated speeds. Whilst applying a time shift to each throw reduced the effect of this time lag, it did not completely eliminate it. Athletes and coaches need to be aware of this limitation when using this type of device in the training environment. Whilst the phase lag was not completely eliminated from the predicted speeds its effect was minimized and the remaining phase lag in the predicted speeds was less than the phase lag evident in the data set of Murofushi et al.⁵ This phase lag is not an issue if the predicted speed data is the only variable being provided for feedback. However, Biomechanists will often utilize video feedback in conjunction with feedback on kinetic and kinematic variables such as speed. As a result, it is important to minimize the phase lag here as peaks and troughs in the predicted speed data will more closely match up with the timing of the video if it is minimized.

5. Conclusion

This study successfully derived and validated a method that allows prediction of linear hammer speed from measured cable force data. Two linear regression models were developed and it was found that either model would be capable of predicting accurate speeds. However, data predicted using the shifted regression model were more accurate. In addition, the method proposed here accounted for the phase lag in the speed data that was evident in data presented in previous studies⁵ that attempted to measure linear hammer speed in the training environment.

References

1. Dapena J, Feltner ME. Influence of the direction of the cable force and of the radius of the hammer path on speed fluctuations during hammer throwing. *J Biomech* 1989;22:565–75.
2. Dapena J. The pattern of hammer speed during a hammer throw and influence of gravity on its fluctuations. *J Biomech* 1984;17:553–9.
3. Brice SM, Ness KF, Rosemond D. An analysis of the relationship between the linear hammer speed and the thrower applied forces during the hammer throw for male and female throwers. *Sports Biomech* 2011;10:174–84.
4. Sanderson LK, McClements JD, Gander RE. Development of apparatus to provide immediate accurate feedback to sprinters in the normal training environment. *New Stud Athlet* 1991;6:33–41.
5. Murofushi K, Sakurai S, Umegaki K, Kobayashi K. Development of a system to measure radius of curvature and speed of hammer head during turns in hammer throw. *Int J Sport Health Sci* 2005;3:116–28.
6. Brice SM, Ness KF, Rosemond D, Lyons K, Davis M. Development and validation of a method to directly measure the cable force during the hammer throw. *Sports Biomech* 2008;7:274–87.
7. Tutevich VN. Teorija sportivnykh metanij. [Theory of the throwing events]. Moscow: Fizkultura i Sport; 1969. [in Russian]
8. Mayagoitia RE, Nene AV, Veltink PH. Accelerometer and rate gyroscope measurement of the kinematics: an inexpensive alternative to optical motion analysis systems. *J Biomech* 2002;35:537–42.
9. Kadaba MP, Ramakrishnan HK, Wooten ME, Gainey J, Gorton G, Cochran GVB. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res* 1989;7:849–60.

