The Interaction Between the Seated Shot-putter and Their Throwing Frame

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ABSTRACT

Seated shot-put is an integral part of the Para Athletics programme. Some ambulant and wheelchair athletes can participate in the seated shot-put event, according to their classification. Seated shot-putters throw from a specialist piece of equipment known as a throwing frame. Athletes are required to remain seated at all times throughout the throwing movement.

Currently, the performance of seated shot-putters depends on the throwing technique whilst using a throwing frame. The comprehensive literature review presented in Chapter 3 investigating 26 articles (1999 – 2020) indicated that the development of the throwing technique could only be partially guided by a limited number of articles focusing on kinematic parameters of upper body segments and the shot-put at release. Unfortunately, most of these studies were conducted before fundamental changes of the seated shot-put rules in 2014 decreasing noticeably their relevance in the current context. Consequently, a better understanding of the interaction between the seated athlete and their throwing frame for performance improvement under the current rules is needed.

The overall aim of this research, through three inter-linked studies (Chapters 4, 5 and 6), was to further explore how some technical-related elements of seated shot-put could influence performance. Release variables along with upper body linear kinematics of elite level athletes were explored to determine which variables were most impactful to performance. The purpose was to provide novel and unique biomechanical evidence showing the impact of various seating configurations (e.g. sitting direction and use of holding pole) on performance.

Critical new insights making contextual links between movement theory and practice for seated shot-putters and their coaches were provided. This work created a milestone advancing evidence-based throwing technique regarding seated configuration valuable to athletes and coaches.

ACKNOWLEDGEMENTS

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Finally, my family and friends for always being there along the way, especially my lifelong partner and soulmate who supports me in in everything I do.

Work to date

Submissions and publications providing background to the thesis

Peer reviewed journal articles

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Submissions and publications arising from and related to the thesis

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Invited Speaker at coaching conferences

O’Riordan A (2018) - Biomechanics of Seated Throwing: Application for Coaches. Oral presentation presented as part of *the British Athletics Seated Coach Forum*, Loughborough University, 27-28 January 2018.

O’Riordan A (2020) - Biomechanics of Seated Shot-put - How seating configuration influences performance: Considerations for Coaches. Oral presentation (virtually) presented at *the Polish Institute of Sport Paralympic Coaches Conference*, Warsaw, Poland, 5 June 2020

Upcoming Publications

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Pre-Amble

This thesis has come about from a 20-year involvement in the coaching of seated throwers. I am an Athletics Australia Master and a UK Athletics Level 3 Performance Throws Coach and began specialising in para throws in 2003 whilst at the Australian Institute of Sport. I have coached multiple medallists onto four Paralympics Games and six World Championships, a number who were also world record holders. Tokyo 2020 will be the 6th Paralympic Games I will have been leading team of athletes from three international nations.

My interest in the biomechanics of seated throwing was initially sparked by the sparsity of research available and knowledge gaps that could inform my own coaching practice. Through my personal coaching experience, from applied research along my journey, and now the completion of this PhD, I have established myself as a world leading expert in both the coaching and researching of seated throwing, not only from my successful coaching record but also through co-authorship of scientific publications that attracted thousands of downloads and multiple citations in relevant literature. I regularly facilitate workshops and present lectures globally for National Paralympic Committees, National Governing Bodies and universities.

1.1 Introduction

This research is interested in the technical related elements of seated shot-put and how they influence performance. Its aim is to explore the interaction of the athlete to their throwing frame, so performance can be improved. Another intention is to provide technical insight to coaches working with Paralympic athletes. However, to improve biomechanical knowledge in this area it is necessary to consider the history and development of seated shot-put, how it evolved from Olympic based shot-put to enable the inclusion of athletes with impairment and becoming part of the Paralympic programme. In particular, the focus is on the biomechanics of seated shot-put including:

- A review of current state of the art knowledge.
- Identification of gaps in the knowledge on seated shot-put technique and the throwing frame, as rules have changed and the event has developed,
- Future directions for a better understanding of the relationship between the athlete and their throwing frame. It is hoped that recommendations can be made to athletes and coaches regarding throwing technique and frame design to impact positively on

performance.

Operational Terminology

There are a number of key phases and positions that make up the seated shot-put throwing pattern, as shown in Figure 2 2.

Starting Position	This is a stationary position at the start of the throwing action, where the athlete prepares by placing the shot-put into their neck. For some seated athletes it might be a front-on position whereby their trunk is facing the direction of the throw. For others it might be a side-on position where the trunk is more diagonal to the throwing direction.
Power position	A term regularly used within shot-put coaching to describe a position where the athlete's bodyweight is positioned over the throwing leg in standing shot-put, and at the back of the throwing frame for seated shot-put.
Non-throwing side block position (NTSB)	The point where the athlete blocks with their non-throwing side either by bracing with a holding pole or by using their non-throwing arm.
Release position	This is the point that the shot-put leaves the throwing hand.
Preparation phase	This phase begins with the starting position and finishes at the power position and is typically made up of a 1st and 2nd preparatory movement. It is the first movement to get the body moving and generate momentum. The 1st preparatory movement usually starts in the forward direction towards the front of the throwing frame (in the throwing direction) and may involve pulling on a holding pole with the non-throwing arm. If a holding pole is not employed, the non-throwing side would be engaged in a more traditional action as seen in standing shot-put. The 2nd preparatory movement continues in a backward direction from the front of the throwing frame to end at the power position.

Completion Phase	This phase starts at the power position and ends at the release position.
Transition Phase	This phase begins at the power position and ends at the Non-Throwing-Side-Block (NTSB), with or without a holding pole.
Delivery Phase	The period that starts at the NTSB and ends at the release position.
Seating configuration	The organisation of the body in relation to the throwing frame.
Performance	The horizontal displacement from the front of the throwing circle to the landing position of the shot-put.
Efficacy	The capacity to impact performance to differentiate the benefits of seating configuration.
Efficiency	A seating configuration was considered efficient when it increased performance.
Performance zone	The rectangle constructed from a velocity time graph where the vertical and horizontal components represent velocity and time, respectively. The shape of the rectangle informs the efficacy.

Thesis Background

The national federation for Para Athletics is World Para Athletics (WPA), who are governed by the International Paralympic Committee (IPC) and co-ordinated by the WPA Sports Technical Committee. Seated throwing events are an integral part of the Paralympic Athletics (Para Athletics) programme. This contrasts with the generic sport of athletics (non-paralympic) which is governed by World Athletics, formerly known as the International Association of Athletics Federations (IAAF). Both wheelchair and some ambulant (standing) athletes can participate in seated throwing events (shot-put, discus, javelin and club throw) and are classified based on gender and functional ability (World Para Athletics 2020-2021), including the control, strength and power of various muscle groups (World Para Athletics 2018).

1.2 Thesis Context

Seated throwing has been part of the Paralympic Programme for over 50 years. Nations are investing increasing resources into athlete preparation in the pursuit of winning medals. Despite this, there is still a lack of research into seated throwing and even less evidenced based coaching related recommendations for improving performance.

In many years as a high-performance coach of seated throwers and as a coach developer, frustrated conversations with athletes and coaches often take place over the lack of evidenced based information that is available. Specifically, challenges experienced in the technical coaching of seated throwers, the lack of knowledge on throwing frame contribution and accessibility issues relating to frame manufacture. Apparently simple contexts, such as what is the most favourable sitting position for the athlete on the throwing frame, and whether a holding pole is needed, are common themes of enquiry.

This thesis intends to focus on the issues above whilst trying to develop a better understanding of the interaction of the seated shot-putter to their throwing frame. It is anticipated that several applied recommendations will evolve from the research which will provide insight to athletes, coaches and support staff to inform technical best practice and throwing frame considerations, to positively impact on performance.

1.3 Thesis Purpose

The purpose is to offer a novel and unique contribution to the area of biomechanics of seated shot-put by providing evidenced based information to athletes, coaches and support staff to allow more informed decision-making regarding throwing technique. Technical aspects of seated shot-putting will be addressed. Consideration will be given to throwing configuration (sitting direction and use of holding pole) and how this might influence release parameters and the movement patterns phases prior to release.

Aspects to allow for greater understanding include to:

- Collate and critically analyse all current research on seating throwing, particularly seated shot-put, to identify gaps in the literature and to provide the basis for the study design.

- Create a specific deterministic model for seated shot-putters based on the conclusions of the literature review and coaching experience.

- Develop methodology to inform biomechanical based research for seated shot-putters and improve the calculation of performance by considering different flight windows of time to formulate velocity at release (Study 1).

- Identify the influence that seating configuration has on the release parameters and thus throwing distance, including which throwing configuration and release parameter/s have greatest impact on performance (Study 2).

- Consider the movement pathway of elite seated shot-putters through the movement phases of the throw and their subsequent influence on the release parameters (Study 3).

- Generate insight to support technical best practice for performance improvements for elite shot-putters and their coaches. The findings need to be applicable and useable to the real world of Paralympic athletics. Coaches and athletes should be able to use the insight to positively influence performance at all levels including major competitions such as the Paralympic Games.

- Provide a visual deterministic model identifying the variables that may positively influence performance. The visual aid is for coaches and athletes to understand and use to inform technical aspects of their training to ultimately improve performance.

1.4 Thesis Aim

The main aim of the thesis is to investigate the interaction between throwing technique and seating configuration, and subsequently the influence of this interaction on performance for seated shot-putters.

Much research identifies a hypothesis with the intention to prove or disprove through the research design. As this research is more exploratory and has multiple conditions, hypothesis statements were not used. Instead a research question was identified, as below.

Research Question

The main research question is:

Is there a universal technique (seating configuration) that could maximise performance of seated shot-putters?

The study was designed to answer qualitatively the following objective:

- Does seating configuration (sitting direction and holding pole usage) influence performance?

This would be addressed through three studies, as shown in Figure 1 1 and included;

- Study 1 – Methods: From pilots to protocol, including:
    - Study 1A – exploration of methodological protocols for ongoing biomechanical testing of seated shot-putters, including kinematic differences of holding pole positioning.
    - Study 1B – methodological protocols for ongoing biomechanical testing of seated shot-putters, including whether throwing configuration influences performance.
    - Study 1C - Calculation of performance: An Error Analysis.
- Study 2 - Seating configuration, shot-put release variables, and performance in elite seated shot-putting.
- Study 3 – Seating configuration, linear movement kinematics, and performance of elite seated shot-putters.

There are methodological similarities between each study, as Study 1 informs Studies 2 and 3. Consequently, there is likely to be some content repetition when reporting the methods as each study is presented independently in its own right.

1.5 Thesis Organisation

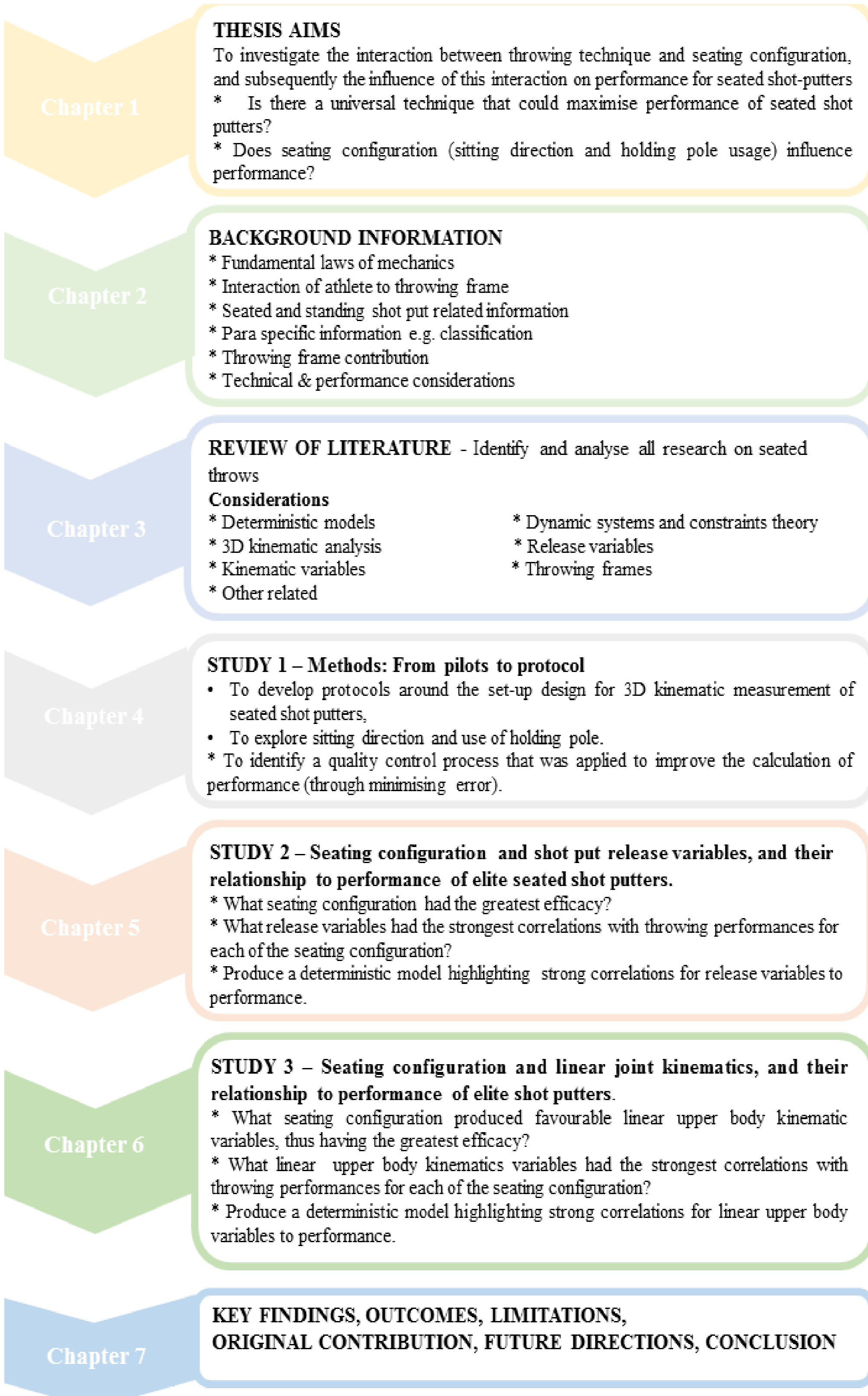


Figure 1 1: Summary of thesis and brief overview of chapters.

1.6 Thesis Structure

This thesis contains a succession of linked chapters, shown in Figure 1 1 and is organised as follows:

- In Chapter 2, more detailed background to Paralympic sport, classification and seated throwing alongside the fundamental laws of mechanics which help explain the interaction between the athlete's technique and the throwing frame. Factors relevant to both seated shot-put throwing technique, throwing frame design and performance will also be discussed.
- In Chapter 3, a broad literature review of 26 articles is presented. It involved a systematic search of all seated throws research. It was conducted with the view to analyse and evaluate the content of all related information to:
    - identify gaps in the literature,
    - inform the study design for this thesis,
    - provide currently absent applied recommendations for athletes and coaching regarding throwing technique and throwing frame characteristics,
    - gain a better understanding of movement pattern information including deterministic models, dynamic systems theory and the constraints approach will be drawn from the related literature.
- Chapter 4 is Study 1 and involved a series of three studies that would inform development of methodological protocols for the subsequent testing. The aim was to develop protocols around the set-up design for 3D kinematic measurement of seated shot-putters, (e.g. the reflective marker locations around the shoulder and pelvis and the number and placement of cameras).

This was achieved by conducting two studies (Study 1A and 1B) involving elite seated shot-putters. It also enabled exploratory data sets to be captured and analysed around seating configurations (sitting direction and use of a holding pole). The results and analyses generated from these feasibility studies were also able to inform protocol for the third feasibility study and Studies 2 and 3.

- Study 1A focused on eight variables including trunk, elbow (on throwing side), shoulder (on throwing side) angle and trunk angular velocity from two holding pole positions.
- Study 1B focused on 16 variables including wrist, elbow (on throwing side), shoulder (on throwing side) and trunk angular velocity from four seating configurations that were determined from sitting direction (front on or diagonal) and use of holding pole (with or without).
- Study 1C involved a quality control process that was applied to improve the calculation of performance (through minimising error). This was done by considering different windows of time to formulate velocity at release (Δ1 and Δ10).

- Chapter 5 is Study 2 and followed a traditional analysis looking at discrete variables that influence throwing performance. This included exploring the influence that seating configuration has on the release parameters, and ultimately throwing distance.

  - Study 2 focused on 40 variables involving the release parameters of vertical, horizontal and resultant velocity, angle, height and gain for all and best throws datasets, from the same four seating configurations utilised in Studies 1B and 1C.

Several statistical analyses were used including coefficient of variation, correlation, linear regression analysis and 2-way ANOVA. Pearson's coefficient r values were used to inform the deterministic model (Figure 3 5).

- Chapter 6 is the third main study and focuses on the movement patterns selected by elite seated shot-putters during the preparation and completion phases, their influence on the flight distance, and ultimately performance (Figure 2 3). Linear kinematics of joints in the trunk and upper limbs on the throwing side were identified alongside temporal variables associated with the key phases within the throwing action. Pearson's coefficient r values were used to inform the deterministic model (Figure 3 5).

  - Study 3 focused on 80 variables including duration of throwing phases, horizontal and vertical displacement and velocity for shot-put/hand, elbow, shoulder (on throwing side) and trunk segments from the four previously identified seating configurations.

- Chapter 7 contains the closing discussion and conclusion. The key findings, outcomes with practical applications, limitations of the research and recommendations for future studies are featured. The practical applications are intended to provide insight for coaches i.e. what can the coach take from the research to implement from a technical aspect to positively impact on performance for elite seated shot-putters. It will include a coaching tool involving the deterministic model indicating the variables with strong correlations to performance.

It should be noted that only the throwing side of the participants was considered for all the studies. Thus, moving forward only the name of the upper limb/segment will be written and not the side of the body, with the assumption that it is always the throwing side that is being referred to. It is also important to emphasise that all three studies are connected. Thus, study 1 informs study 2 which informs study 3. As each study is written in a traditional article format, there may be some repetition especially within the methods sections.

Chapter 2: Background

2.1 Introduction

This chapter provides background information on seated shot-put. It has been included because seated shot-put has specific impairment and Paralympic considerations that impact on it as a sport event and a topic of research, which are often not known or understood. Thus, it makes it different from its standing non-disabled counterpart.

To begin with, some general disability information that impact on research in this area is discussed. The fundamental laws of mechanics will assist in understanding how seated shot-put performance is determined by the interaction of an athlete's technique to their throwing frame (Figure 2 1). Seated shot-put will then be explained, including how it developed from Olympic shot-put and progressed over time influenced by the rules of the event. Factors impacting on both seated shot-put throwing technique, throwing frame characteristics and performance will also feature.

It is important also to highlight some important constraints when working with elite disabled participants. These are likely to influence any proposed biomechanical analysis and are different from usual research practices when working with a non-disabled population. Adult disabled people of working age make up only 19% of the population of the UK (Department for Work and Pensions UK 2018, Family Resources Survey 2016/17). Consequently, there will also be fewer numbers of elite performers in the disabled population than in non-disabled and this will influence the number of participants that will be able to participate in any research. However, the percentage of participants per specific population needs to be considered.

Similarly, many people with physical impairments, particularly spinal cord injury, experience higher levels of fatigue than the general population (Craig, Tran, Wiliesuriva and Middleton 2012). This will likely affect the number of trials that a participant may be able to conduct under maximal conditions. Thus, aligning the in-lab to in-competition is important especially around the number of throwing trials. These factors of numbers and impairment related fatigue levels are likely to have an impact on the statistical power of any disability related research.

According to the fundamental laws of dynamics, the movements of the centre of mass of a multi-body system (Sa) depends on the summation of all external forces applied on this system. At a given instant t, this relation can be described by:

$$\sum \overrightarrow{Fext} = \frac{d\overrightarrow{L_{G/GCS}}}{dt}$$, in translation (Equation 1), and by

$$\sum \overset{\cup}{M_O}(\overrightarrow{Fext}) = \frac{d\overset{\cup}{A}_{G/GCS}}{dt}$$, in rotation (Equation 2).

The left terms of Equations 1 and 2 are associated with the displacement of the centre of mass of the whole body.

The term $\overrightarrow{L_{G/GCS}}$ (in Equation 1) is the linear momentum of the system Sa in the GCS, and is equal to $Ma\overrightarrow{V_{G/GCS}}$ where $\overrightarrow{V_{G/GCS}}$ is the velocity of the centre of mass G in the GCS. Since the system Sa can be characterised by its centre of mass $\overrightarrow{OG}$ obtained by

$$\overrightarrow{OG} = \frac{\sum_{i=1}^{16} m_i \overrightarrow{OGi}}{\sum_{i=1}^{16} mi},$$

the term $Ma\overrightarrow{V_{G/GCS}}$ is equal to $\sum_{i=1}^{16} mi\overrightarrow{V_{Gi/GCS}}$. Thus, $\overrightarrow{L_{G/GCS}} = \sum_{i=1}^{16} mi\overrightarrow{V_{Gi/GCS}}$.

The term $\overset{\cup}{A}_{G/GCS}$ (in Equation 2) is the angular momentum of the system Sa of O in the GCS, which is equal to $\sum_{i=1}^{16}(\overrightarrow{OGi} \wedge mi\, d\overrightarrow{V_{Gi/GCS}})$. In the case of the shot-put, the instantaneous velocity of the centre of mass of the system changes over the time. Consequently, $\sum_{i=1}^{16} mi\overrightarrow{V_{Gi/GCS}} = \sum_{i=1}^{16}(\overrightarrow{OGi} \wedge mi\, d\overrightarrow{V_{Gi/GCS}})$ varies at each given instant t.

The right terms of Equations 1 and 2 are associated with the external forces applied to the system Sa. In principle, these external forces are due to the interaction between the system and its environment. These interactions include the weight as well as all points of contact between the athlete and external objects such as the throwing frame and the shot-put.

Pre 2014 rule change (Table 2 2), the number of contacts with the throwing frame and their surface varied between athletes depending on their impairment, technique and the design of the throwing frame. However, current rules (post 2014) are such that typically athletes are required to be in contact with the seated area of the throwing frame at all times, from their ischial tuberosity to the back of their knee, which simplifies things somewhat.

Consequently, external forces applied to the athlete are:

- The weight of the athlete ($\vec{Wa}$), having A_G as point of application and obtained by $\vec{Wa} = Ma\,\vec{g}$ where $\vec{g}$ is the vertical acceleration.

  $\overset{\cup}{Mo}(\vec{Wa})$ is the moment of the weight in relation to the point O.

- The reaction force of the holding pole on the athlete ($\vec{R}_{R4A}$) having the centre of pressure of the surface of contact of hand with the pole as point of application. $\overset{\cup}{Mo}(\vec{R}_{R4A})$ is the moment of this reaction force in relation to the point O.

- The reaction force of the shot-put on the athlete ($\vec{R}_{R5A}$) having the centre of pressure of the surface of contact of hand with the shot-put as point of application.

  $\overset{\cup}{Mo}(\vec{R}_{R5A})$ is the moment of this reaction force in relation to the point O.

The exact mass M of the system S must be measured as accurately as possible. Consequently, the mass of the shot-put and athlete must be known just prior to the recording of the kinematic data. The rest of the anthropometric information needed such as the mass, the centre of mass and the moment of inertia of the whole body and of each segment will be obtained using the computer software within the 3D analysis system, and is based on anthropometric tables as presented in Winter (1991).

The kinematics data necessary to calculate the terms:

$$\frac{\sum_{i=1}^{17} mi\, d\vec{V}_{Gi/GCS}}{dt} \text{ of Equation 3 and}$$

$$\frac{\sum_{i=1}^{17} d(\vec{OGi} \wedge mi\, d\vec{V}_{Gi/GCS})}{dt} \text{ of Equation 4,}$$

should be obtained in 3D using a motion analysis system. The procedure needed to obtain the displacements in 3D and the relevant marker set is well described in the literature ((McGinnis

2005; Payton and Bartlett 2008; Richards 2008).

Thus, the left side of the equations are associated with the kinematics of the body, i.e. the throwing technique. The right side involves the dynamic (external forces) connected with the equipment i.e. the throwing frame. Subsequently, this highlights that the interaction of athlete throwing technique to the throwing frame becomes a critical component of the outcome i.e. the performance, represented in Figure 2 1.

With the current rules of the event in place (Table 2 2) many aspects of this interaction are constraints led. Thus, considering a constraints-led approach of dynamical systems theory (DST) is necessary with insight on what this means for the coaching of seated shot-put (Figure 3 2). A DST approach will be novel and unique to any biomechanical analyses on seated throwing and is discussed in detail in Chapter 3.

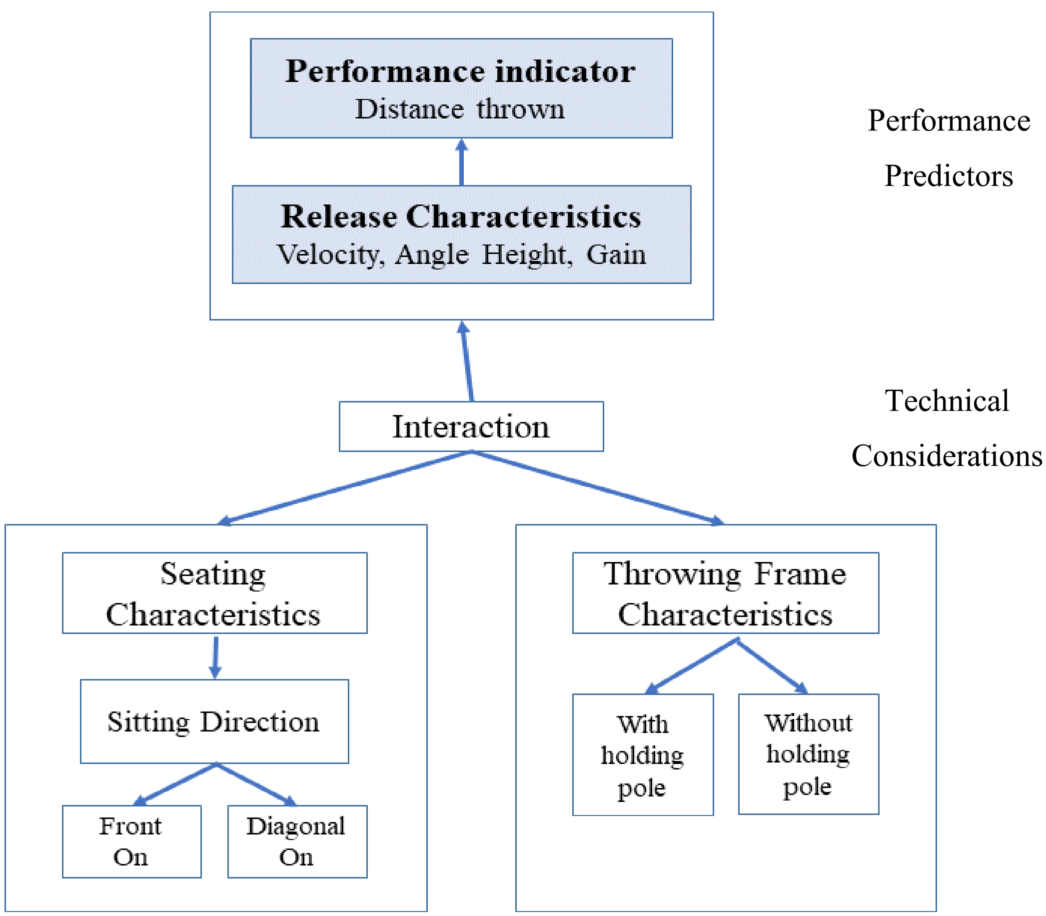


Figure 2 1: The interaction of seating and throwing frame characteristics and how they influence performance.

Description of Seated Shot-put and Shot-put

Generally, throwing movements often involve over, under or side arm actions (Bartlett and Robins 2008 in Hong and Bartlett 2008). Shot-put differs slightly from other throwing movements as it technically is not a throw but a put. This is because the event rules stipulate that the shot-put cannot drop below the shoulder line of the athlete at any point during the throwing action (World Athletics 2019). The main aim of the shot-put event is to throw for distance, and the force applied to the shot-put throughout the throwing movement is essential to influence the release speed. The latter is considered to be the most important factor when throwing for distance (Bartlett 2007).

Shot-put is one of the four throwing events (shot-put, discus, javelin and hammer) included in Olympic competition programmes. For this thesis it will be referred to as standing shot-put and/or throwing. In the open Olympic (senior) classes of standing shot-put the males throw a 7.26kg shot, whilst females throw 4kg.

Seated shot-put is derived from Olympic Shot-put and is one of the four seated throwing events included in Paralympic competition programme. For this thesis, it will be referred to as seated shot-put and/or throwing. Shot-put weights for senior aged athletes vary within seated shot-put due to functional differences and for safety purposes, as shown in Table 2 1.

Table 2 1: Official shot-put weights used by seated shot-putters.

Athletes with SCI, limb deficiency or leg length difference	Male	Female	Athletes with coordination impairment	Male	Female
F52	2kg	2kg	F32	2kg	2kg
F53	3kg	3kg	F33	3kg	3kg
F54, F55, F56, F57	4kg	3kg	F34	4kg	3kg

Historically, seated shot-put has been the most popular throwing event at Paralympic Games since Sydney 2000, with the greatest number of athletes from more countries competing. There are 29 seated throwing events (shot, discus, javelin and club) scheduled for the 2020 (+1) Tokyo Paralympic Games, with 14 (seven male and seven female) of them being seated shot-put.

2.2 Contribution of Throwing Frame

During a seated shot-put competition, each athlete can use their own throwing frame. Throwing frames have a number of necessary features or characteristics that have been described previously (Frossard, O'Riordan and Goodman 2010), and include seat size and shape, footplates/rest, holding pole positioning, strap placement, and maneuverability (Figure 2 2). The construction of the throwing frame is intended to maximise performance, whilst the individual athlete's functional ability is accounted for. To date, this has largely been driven by a trial-and-error approach and access to available resources (Frossard, O'Riordan and Smeathers 2012a). Therefore, if the effect of throwing frame design on technique, and subsequently performance, is known, more favourable throwing frames can be efficiently constructed.

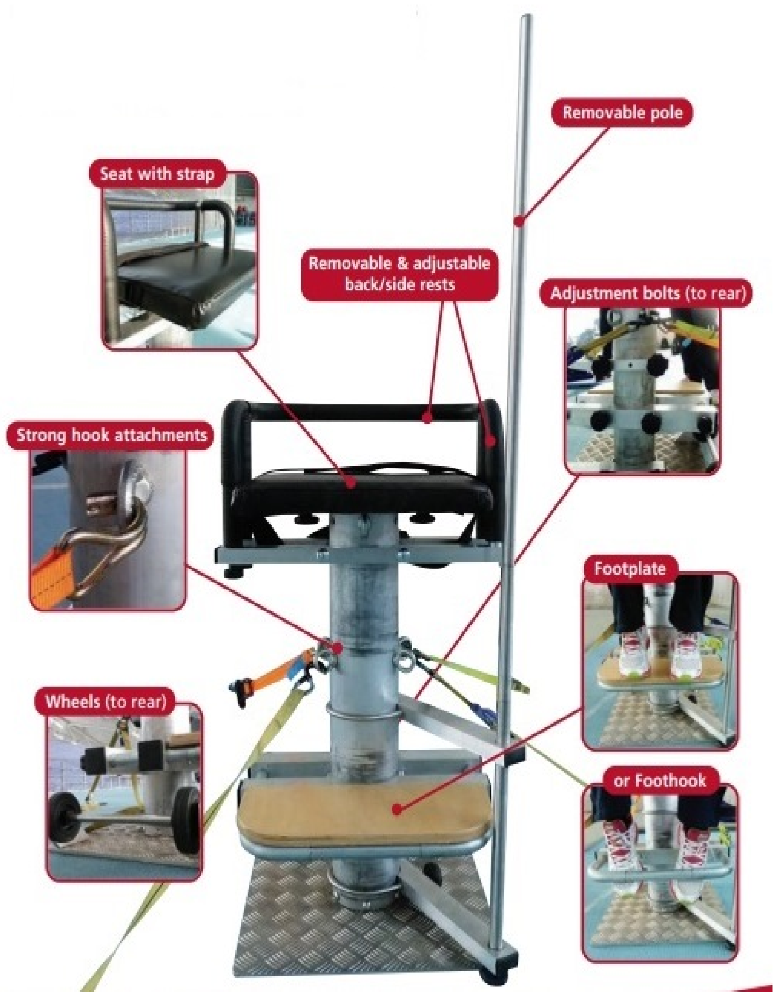


Figure 2 2: Example of commercially available adjustable throwing frame, showing features such as a pole and footplates - (https://www.englandathletics.org/disability-athletics/equipment-and-funding/protean-seated-throws-frame.

Organism-led constraints' on throwing frame design (Figure 3 2) have increased dramatically since 2003 where there has been three important changes in the rules of the event (Table 2 2). Pre 2014 there were less constraints on throwing frame design which meant more opportunity to maximise athlete function by designing a frame that facilitated this. The additional 2014 constraints have impacted dramatically on throwing technique and performances thus making some of the earlier research only partially relevant in the current context. Seated shot-put performance has been identified to depend on the interaction between athlete technique and the throwing frame. Now that throwing frame design has become less important due to the increased constraints it is likely more emphasis needs to be placed on the understanding of seated shot-put technique as the main contributor to performance.

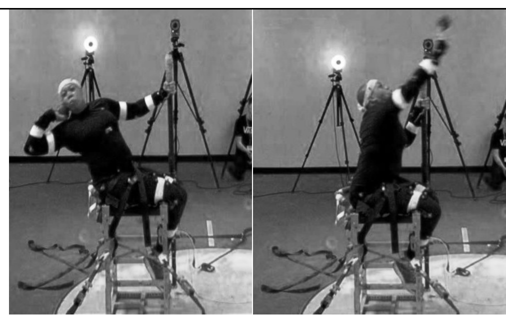
The rules currently relating to throwing frame design include:

- the maximum height of the seating area from the ground should not exceed 75cm and must be square or rectangular in shape, with a minimum surface area of 40 x 40 cm.
- the controlling of the types of material and additional mechanisms used that could assist the athlete during the throwing action, although a "rigid" pole is allowed for stabilisation (Figure 2 2).

Longitudinal seated throwing research took place at the Australian Institute of Sport, during the period 2003 – 2011. It included the design of a new fully adjustable throwing frame, which I developed alongside sports engineers. Despite being designed for research, it was also used in competition as it complied with WPA rules at the time (Figure 3 3). The more commercially available throwing frame in Figure 2 2, was also designed by myself and has been purchased by athletes and athletics clubs worldwide.

It is the adjustable designs of these throwing frames that make them valuable for both research and for everyday athlete use. Adjustable frame characteristics such as holding pole, feet and/or back rest position could be manipulated to accommodate individual athlete requirements. An adjustable frame that all athletes could use, would decrease the competition time. It might also "level the playing field" with regards to throwing frame availability. This would be especially relevant to those poorer nations without resources to research, design and construct state of the art throwing frames.

Table 2 2: Summary of rule changes over time for seated throwers.

		Throwing Technique	Throwing Frame Design
Pre 2008		• Athlete to remain in contact with the throwing frame at all times by the back of one knee. • No other restrictions placed on throwing technique. Some athletes with available function would start and finish their throwing in a standing position.	• Maximum height = 75cm • No restrictions on shape or size of seating area • A holding pole could be used of any shape or style. • Footrests/plates and backrest could be used.
2009 – 2014		• Athlete able to start in a seated position and allowed to finish in a standing position as long as the sitting to standing action took place during the final forward movement (during the completion phase). • Athletes to have feet on the floor during the throwing action. • Athlete to remain in contact with the throwing frame at all times by the back of one knee.	• Maximum height = 75cm • No restrictions on shape or size of seating area • A holding pole could be used of any shape or style but should be rigid. • Footrests/plates and backrest could be used.
Post 2014		• All athletes must start and finish in a seated position remaining in contact with the seat from the back of knees to ischial tuberosity	• Maximum height = 75cm • Square or rectangle seating area (min of 30x30cm), level or sloping backwards. • Holding pole should be one rigid vertical piece and should not bend. • No moving parts.

2.3 Contribution of Technique

Since the 2014 rule change, throwing technique has become more important in influencing the interaction of the throwing technique and frame for better performance, whilst the influence of throwing frame design has declined. Rules have impacted on technique (Table 2 2), but other para specific factors such as classification, are also important. These will be discussed here alongside technical considerations specific to seated shot-put.

The rules which currently impact on throwing technique include:

- remaining in contact with the throwing frame at all times throughout the throwing movement, from the back of the knee to the ischial tuberosity.
- the sitting position must be maintained throughout the throwing action until the throw has been marked.
- time restrictions for athletes to get onto their throwing frames and begin their throwing trials.
- time limits on completing each throwing trial.

Classification

Athletes are assessed on their available function and assigned to classes, through a process known as classification which is unique to para sport (World Para Athletics 2018). The two main aims of the WPA classification system are to determine eligibility to compete, and to allocate athletes into groups for competition, based on similar activity limitation levels because of their impairment. These groups are given a number based on impairment and activity limitation.

Seated throwers with spinal cord injury, limb deficiency or leg length difference compete in Classes F51 to F57 and those with co-ordination disorders in Classes F32 to 34. The F indicates a field discipline whilst the 5 notates athletes with spinal cord injury (SCI), limb deficiency or leg length difference and the 3 notates co-ordination disorders. The degree of activity limitation within those impairments is represented by the number following the 5, or 3 (Table 2 3).

The F55 classification is of interest, as athletes in this class typically have partial to full trunk muscle power. The class sits between the F54 and F56 classes with the former having no trunk power and the latter, full trunk power (World Para Athletics 2018). It should be noted that athletes in classes F54, F55 and F56 all have full arm function. Differences in seating configuration (sitting direction and use of holding pole) are mostly seen amongst the competing athletes in the F55 classification. Athletes in the less functional class (F54) tend to all use a holding pole when throwing (see Figure 4 2**).** Athletes in F56 class and above, often do not. This might then suggest that the available trunk muscle power becomes a significant factor in a chosen seating configuration.

Table 2 3: Overview of classification according to level and type of impairment within Para Athletics for seated throwers.

	Athletes with spinal cord injury	Athletes with limb deficiency or leg length difference	Athletes with co-ordination disorders
High	F51		
Activity Limitation ↑	F52		F32
	F53		F33
	F54		F34
	F55		
	F56	F56	
	F57	F57	

There are limited technical recommendations currently available informing athletes and coaches as to favourable seating configuration based on athlete trunk muscle power. It is one of the intentions of this research to provide insight that might inform such recommendations. Thus, the main focus will be on athletes in F55 and F56 as partial to full trunk muscle power seems to be the point that technical and throwing frame differences begin to be more visible.

Technical Considerations for Seated and Standing Shot-put

Since seated throwing is derived from standing throwing, it is necessary to consider standing shot-put technique as it has been a well researched activity over many years, leading to some relatable literature. Similar body positions are seen between the seated and standing event including the start, power, non throwing side block (NTSB) and release (Figure 2 3). However, there are differences with the most obvious one being between standing and sitting.

Another difference occurs with the type of movement during the preparation phase, and how the athlete moves from the start to power positions. Seated shot-putters are generally facing forwards or slightly diagonal and conduct several linear movements forward and back with their trunk and upper body, before arriving into the power position. Whereas, standing shot-putters usually start facing backwards to the throwing direction. They drive linearly or rotationally with their lower body into the power position at the centre of the circle. Because of the clear differences in the two versions, biomechanical analyses on standing shot-put are only partially relevant, so separate, specific analysis is needed to fully understand the seated shot-put event.

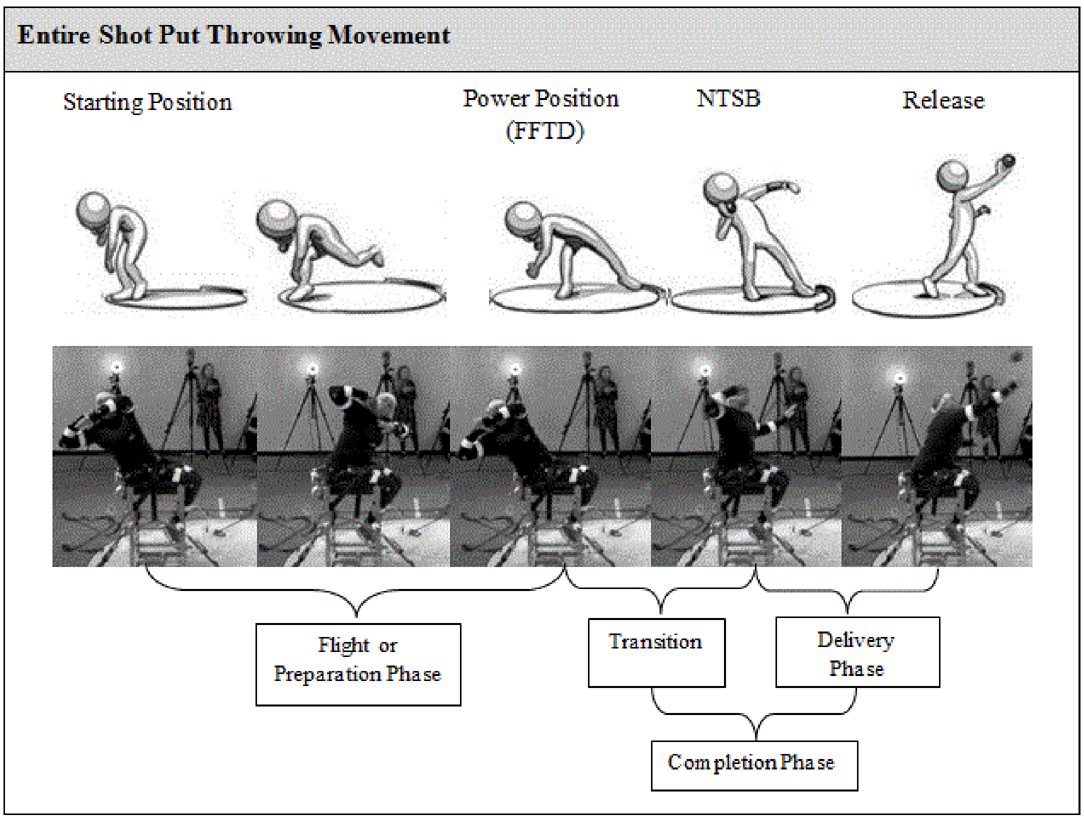


Figure 2 3: Comparative technical breakdown highlighting common technical aspects between seated and standing shot-put. (FFTD: First foot touch down, NTSB: Non-throwing side block).

There are generally two main throwing techniques associated with standing shot-put, the glide and rotational techniques. At the 2017 IAAF World Championships in London, all the top eight male shot-putters used the rotational technique. However, in the female shot-put event only three of the eight finalists (37%) used the rotational technique, with the five other athletes (63%) using the glide technique, including the gold and bronze medallists. This shift, especially amongst male competitors, from the glide to rotational technique requires further research exploration. A USA Track and Field report (adapted from articles written by Young and Li 2005 and Terzis, Kyriazis, Karampatsos & Georgiadis 2012) suggests that the rotational technique is more suited to those athletes with less overall strength but more power.

A descriptive study was conducted by Frossard, O'Riordan and Goodman (2010) whereby a catalogue of throwing frames characteristics used by seated shot-putters (215 throwing trials of 55 male athletes) during the 2006 IPC Athletics World Championships. The cataloguing involved defining and clustering 26 characteristics into three main groups including whole body, legs and upper limb specific characteristics. The data provided valuable information on seating configuration and how this differs between athletes and across classifications.

This work contributed to identifying two main throwing techniques for seated shot-put, determined by seating configurations, including sitting direction (front on or diagonal) and the use of a holding pole (with or without holding pole). At the 2017 World Para Athletics World Championships in the F55 shot-put events, 75% of the male and 78% of female athletes threw from a front on with a holding pole. The other athletes also threw from a front on sitting direction but did not use a holding pole. This brief analysis was produced by watching video footage from the chosen championships.

The technical breakdown of seated shot-putters has not been analysed in detail. It has been done descriptively for an athlete with cerebral palsy (O'Riordan and Frossard 2006). Although completed with one athlete in a single (functional) class and according to older rules which influenced sitting position and throwing frame design, much of the technical breakdown was relevant for other para throwers at the time.

Further, a generic technical model has also been described within a coaching guidance document on wheelchair athletes (O'Riordan 2015). Both of these information sources provide guidance to the coach and athlete on key technical positions and allows for the technical movement pattern to be developed by describing the sequencing of the athlete's body segments in the various phases from the power position until release of the shot-put. It is important to note, these technical models for seated shot-putters (O'Riordan and Frossard 2006; O'Riordan 2015) have generally been developed by comparing it to the standing one, and the guidance is based on largely descriptive information derived from coaching experiences and not from an evidenced based research process.

2.4 Performance considerations

As shown in Figure 2 4, predictors of performance include the release characteristics (velocity, angle, height, gain) and how they influence the performance indicator (distance thrown). To understand the importance of the release variables, the throwing mechanics of shot-put need to be considered.

Very early research applied basic mechanical principles to the shot-put describing the requirements for putting for maximum distance requiring the athlete to release the shot-put with maximum velocity at an optimum angle and height (Pagani 1981). The acceleration of the shot-put should gradually increase into the release (Vigars 1979) through timely summation of force application from larger, slower muscles (i.e. the legs and hips for standing throwers, and the trunk for seated throwers) to the smaller, weaker muscles of the arms and wrist (Pagani 1981).

Maximum throwing power has been claimed to involve the carefully organised control of acceleration and deceleration of multiple body segmental movement in the proper sequence. This sequencing allows for maximum velocity to be transferred to the throwing hand (O'Shea and Elam 1984). Maximum velocity of the last segment, the hand, should be at its maximum close to the release, and not at release as maybe assumed. This is because by decelerating the non-throwing side prior to release will increase the acceleration of the throwing side (Arial 1979). Although these throwing principles are aged they are still utilised today within both the standing and seated shot-put event. To avoid repetition, the flight characteristics of the shot-put, the theory relating to the release characteristics and their relationship are explained in Study 1C, Study 2 and Study 3, respectively.

Application to the coaching of seated shot-putters

Currently, the rules of seated shot-put are controlled by WPA which impose several constraints as detailed in their 2020-21 Rules and Regulations. Of importance is the impact the current rules constraints have on the coaching of seated shot-putters (Table 2 2). All factors relating to coaching seated shot-putters are shown in Figure 2 4. They are considered as within (internal) or outside (external) the control of the coach.

Internal Factors - those under the coaches' control

Most relevant are the factors directly under control of the coach defining their actual contribution to athlete performance. These include technical decisions made on sitting direction and use of holding pole, along with training interventions around physical preparation and skill acquisition. It is the technical decisions on sitting direction and use of holding pole, referred to as seating configuration that will be the main focus for this thesis. However, there is still no evidenced based information to inform coaches and athletes to what is the most efficient seating configuration to influence performance.

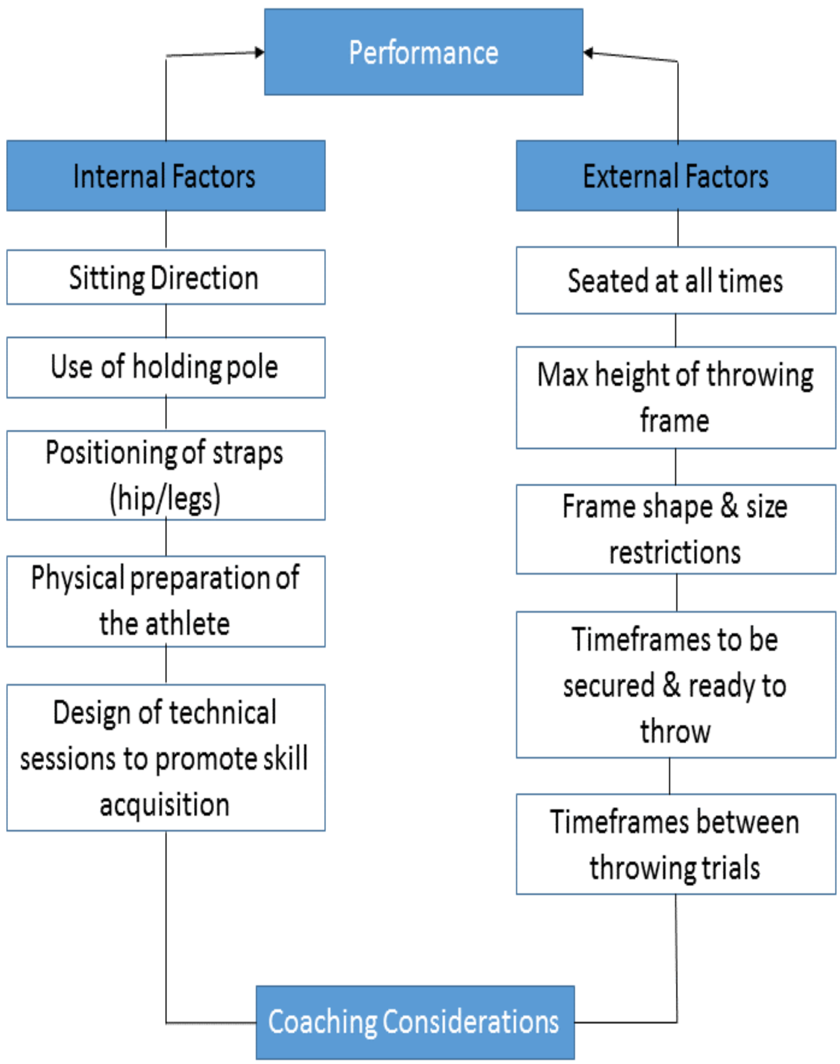


Figure 2 4: External and internal factors framing the coaching of seated shot-putters.

External Factors – those outside the coaches' control

The most important of the technical rules requires the athlete to sit at all times throughout the throwing movement with both legs in contact with the seat surface of the throwing frame. Consequently, athlete function for some has been limited potentially reducing the importance of throwing frame design that might enable functional capacity. This has meant that throwing frame design has become more standard, perhaps becoming of lesser importance for the internal coaching factors.

Chapter 3: Review of Literature

The content of this chapter will be presented in the following publication:

O'Riordan A and Frossard L - Biomechanics of Seated Throwing: A review of literature. To be submitted to *Adapted Physical Activity Quarterly* in January 2021.

Abstract

Purpose: To provide an overview of biomechanical studies relating to Paralympic seated throwing. ***Methods***: The following search terms (biomechanics OR kinetics OR performance), AND (seated OR secured OR stationary OR wheelchair) AND throwing, AND (Paralympics OR Disabled) NOT Injury were entered into the Middlesex University Summon electronic database. After screening, 26 studies relating to seated throwing were reviewed and placed into seven clusters for further analysis. ***Results***: The analysis highlighted there was limited research involving 3D data collection (n=4) and that most research (n=23) is pre the 2014 rule change which affected both technique and throwing frame design, so is only partially relevant at this time. There was more research on the release variables when compared to kinematic variables. This was even more evident for the linear kinematics of upper body segments and their contribution to the seated shot-put throwing pattern. Finally, there are limited technical recommendations generated for athletes and coaches. ***Conclusions***: A better understanding of the interaction between the seated thrower and their throwing frame and how this influences performance is needed. This is particularly so since the introduction of new rules implemented by World Para Athletics in 2014, which saw both technical and throwing frame constraints changing. An updated deterministic model for seated shot-put was constructed based on the literature review. Its intention was to provide an evidence-based tool to inform technical decision making by seated throws coaches.

3.1 Introduction

Currently, decisions made by seated athletes and their coaches regarding throwing technique frame characteristics are mainly based on anecdotal evidence e.g. comfort, trial and error (Frossard, O'Riordan and Goodman 2005). Throwing frame design is critical as it has the potential to influence the organism-led constraints (functional level) which would lead to changes in the co-ordination strategy, and hopefully maximum performance (Keogh 2011). A better understanding of the interaction between the seated athlete and their throwing frame is needed (Keogh and Burkett 2016). This could enable evidenced based decisions regarding throwing technique and frame design by the coach and athlete, to influence performance.

Seated throwing as an activity could be considered as generally under researched with little understanding of the technical requirements needed to improve performance. Thus, the intention was more about identifying all related literature and undertaking initially an unbiased critical review of all existing research, as this has not been done previously. For this reason level of evidence will not be assessed, although study type is identified and included in the relevant tables of information (Table 3 2 - Table 3 8).

The purposes of this literature review were to establish the current state of knowledge on seated throwing with a view to highlighting the gaps in the knowledge. It was anticipated that by investigating the approaches mostly used they would help educate the design of the methodology for this thesis. They should also assist with understanding the interaction between athlete technique and their throwing frame.

3.2 Methods

A comprehensive systematic search of all research on seated throws was employed. The following search terms (biomechanics OR kinetics OR performance), AND (seated OR secured OR stationary OR wheelchair) AND throwing, AND (Paralympics OR Disabled) NOT Injury; were entered into the Middlesex University electronic database named Summon. Google Scholar was used to search for any other seated throws articles, known by the author. All articles that contained any type of information relating to seated throwing, at any level of status (recreational to elite) were included.

The Summon database searches all other databases that the university accesses, which include Cochrane, Medline, PubMed, Sage Journals Online, Sports Discus. These are the main databases that are considered for sports related research. Only full papers written in English were included, and the search was conducted up until October 2020. All study types were considered including randomised trials, descriptive, evaluation, reports, and systematic reviews. Several articles were excluded (n=92) after screening (Figure 3 1). They were excluded if they focused on any of the following areas not directly related to seated throwing including:

- general biomechanics
- biomechanics of other throwing/striking sports
- biomechanics of Olympic throwing events
- general throwing
- other para biomechanics
- other para sports.

Based on the above criteria, 26 articles were retained (Figure 3 1 and Table 3 1) including a small number of articles (n = 3) discussing relevant aspects such as the role of biomechanics of Paralympics sports (Table 3 3). All articles were inputted into an excel spreadsheet for comparison and to facilitate identification of study type, topic/research questions, number of participants, testing procedure, method of data capture, design (variables), statistics, outcome measures, results, conclusions, strengths, limitations, opportunities for further study. Based on commonalities amongst the research and critical aspects of seated shot-put, the articles were then placed into clusters around the following topics including:

- Cluster 1 (n = 3) - research involving deterministic models
- Cluster 2 (n = 3) - the role of biomechanics in Paralympic sport
- Cluster 3 (n = 4) - research that used 3D capture and analysis
- Cluster 4 (n = 9) - research focusing on release variables
- Cluster 5 (n = 7) - research focusing on kinematic variables
- Cluster 6 (n = 9) - throwing frame related research
- Cluster 7 (n = 11) - other research on seated throws aspects such as throwing movement, technical coaching, classification and seating pressure.

The articles are inputted into the cluster tables in chronological order. If an article covered a variety of research areas, it appears across a number of different clusters. This meant possible repetition across the clusters, although this was kept to a minimum as much as possible. Table 3 1 shows the frequency of papers across the clusters. There is obvious overlap but not too many strong duplicates between the clusters which demonstrates that each cluster can be a stand-alone topic. The research of Frossard, O'Riordan and Goodman (2005) has the highest frequency (four) across the clusters.

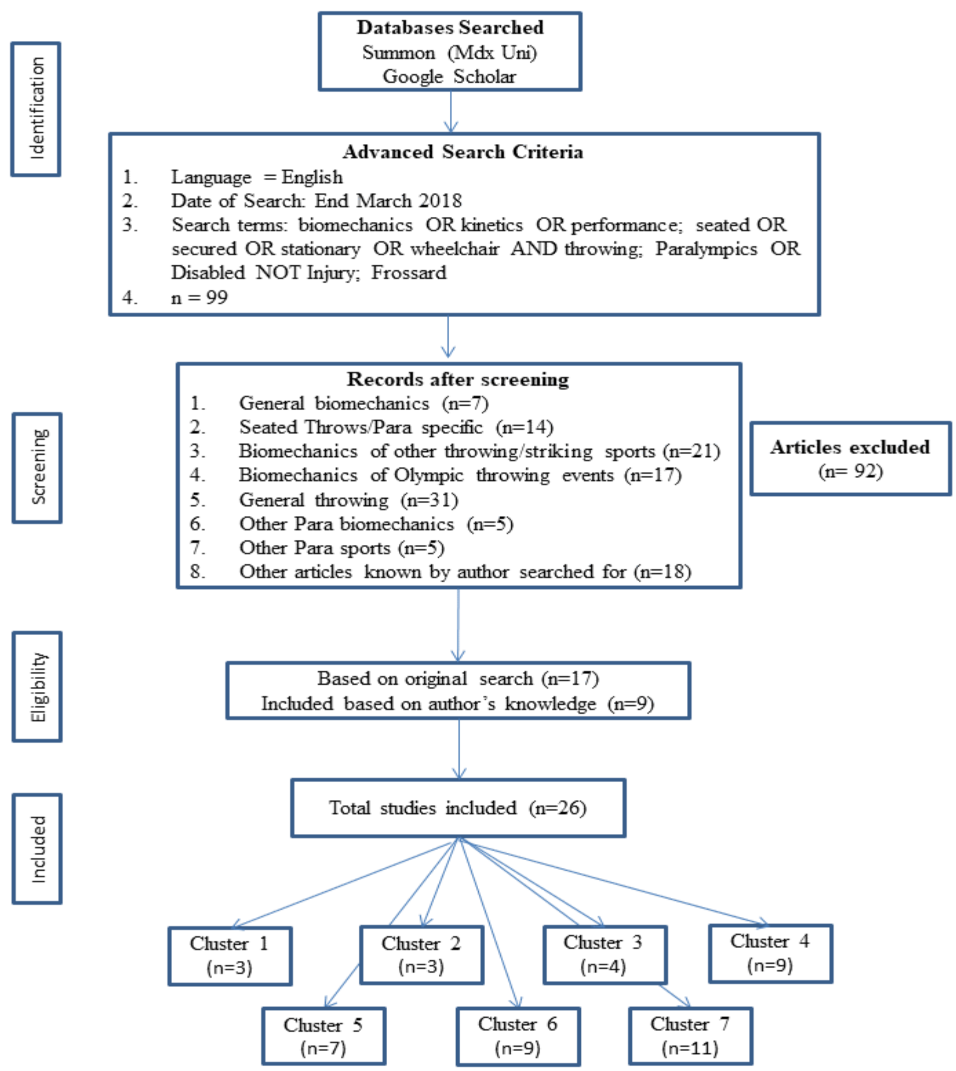


Figure 3 1: Flow diagram of the systematic search.

Table 3 1: Distribution of selected references by clusters.

Study	**Cluster 1** Table 3 2 Deterministic models (n = 3)	**Cluster 2** Table 3 3 Biomechanics in Para sport (n = 3)	**Cluster 3** Table 3 4 3D capture and analysis (n = 4)	**Cluster 4** Table 3 5 Release variables (n = 9)	**Cluster 5** Table 3 6 Kinematic variables (n = 7)	**Cluster 6** Table 3 7 Throwing frame related (n=9)	**Cluster 7** Table 3 8 Other seated throwing aspects (n=11)	**TOTAL**
Abdelkader, Madani and Bouabdellah (2020)					X			**1**
Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx, Tweedy (2016)			X		X			**2**
Chow & Mindock (1999)	X			X	X			**3**
Chow, Chae, Crawford (2000)	X			X	X			**3**
Chow, Kuenster, Lim (2003)	X			X	X			**3**
Chung, Lin, Toro, Beyene, Garcia (2010)						X		**1**
Curran & Frossard (2012)							X	**1**
Freitas, Abreu, Souza, Donega, Araujo (2015)						X	X	**2**
Frossard, Stolp, Andrews (2004)							X	**1**
Frossard, O'Riordan, Goodman (2005)			X	X	X	X		**4**
Frossard (2006)							X	**1**
Frossard, Smeathers, O'Riordan (2007)				X			X	**2**
Frossard, O'Riordan, Goodman (2009a)				X		X	X	**3**
Frossard, O'Riordan, Goodman (2009b)				X		X	X	**3**
Frossard, O'Riordan, Goodman (2009c)				X		X		**2**
Frossard, O'Riordan, Goodman (2010)						X		**1**
Frossard, O'Riordan, Smeathers (2012a)							X	**1**
Frossard, O'Riordan, Smeathers (2012b)							X	**1**
Frossard (2012)							X	**1**
Grindle, Deluigi, Laferrier, Cooper (2012)						X		**1**
Keogh (2011)		X						**1**
Keogh & Burkett (2012)		X						**1**
Lee, Davis, Judge, Kwon, Han, Kim et al. (2015)			X	X				**2**
Morrien, Taylor, Hettinga (2016)		X						**1**
O'Riordan & Frossard (2006)							X	**1**
Tweedy, Connick, Burkett, Sayers, Meyer, Vanlandewijck (2012)			X		X	X		**3**
TOTAL	**3**	**3**	**4**	**9**	**7**	**9**	**11**	**46**

3.3 Findings and Discussion

Cluster 1: Deterministic models

A strength of very early research into seated throwing (Chow and Mindock 1999; Chow, Chae and Crawford 2000; Chow, Kuenster and Young-tae 2003) were the detailed deterministic models that the authors developed for each of the seated throwing events. They were based on original sports related modelling (Hay and Reid 1982, Hay 1993), and are shown in Table 3 2. Only information relating to deterministic modelling will be presented here. The release and kinematic variables from the studies will be discussed in subsequent clusters 3 and 4. Consequently the information relating to these other variables is shadowed in Table 3 2.

Deterministic models are a modelling pattern that identify and determine the relationship between biomechanical factors that are responsible for a movement outcome (Lees 2002; Chow and Knudson 2011). They are often presented graphically to be as user-friendly as possible, especially when used in an applied context, as with athletes and coaches (Bartlett 2007). They have been used frequently across sports research including discus throwing (Hay and Yu 1994), long jumping (Hay, Miller and Canterna 1986), soccer kicking (De Witt and Hinrichs 2012), golf (Hume, Keogh and Reid 2005), baseball (Gray 2009,) as well as seated discus, shot-put and javelin (Chow and Mindock 1999; Chow, Chae and Crawford 2000; Chow, Kuenster and Young-tae 2003).

The deterministic model specific to seated shot-put as presented by Chow, Chae and Crawford (2000), was relevant to the rules governing the throwing technique at that time. Athletes were allowed to finish in a standing position provided that the back of one leg remained in contact with the throwing frame at all times. This meant that there was minimal hip motion utilised during the throwing action (Chow, Chae and Crawford 2000). However, viewing of athletes competing and personally coaching seated throwers at this time, indicated otherwise. If the leg in contact with the throwing frame was the brace leg on the non-throwing side, then the athlete was able to utilise their hip on their throwing side in a similar way to a standing thrower. Indeed, many athletes at that time often released the implement in a standing position, clearly using both legs and hip to assist the throwing movement.

The deterministic model of Chow, Chae and Crawford (2000) identified a five linked segmental model between the hips and the shot-put including the trunk, shoulder girdle, the upper arm, the forearm and the hand and claimed that the kinematics of the shot-put were determined by the angular kinematics of these five segments. Advantages of such modelling include the identification of relevant aspects that might impact positively on performance, allowing for the biomechanical analysis to be more exact. It was considered important to update and refine the deterministic model to consider the latest rules (e.g. the consistent sitting position imposed throughout the throwing action). As athletes are now unable to finish in a standing position, as previously, this could potentially place more importance in other areas, including the influence the trunk might have on the throwing movement (Figure 3 5).

Limitations to the deterministic model proposed by Chow and Knudson (2011) have been raised by Glazier and Robins (2011) who state it only details what the performance parameters are and not how they interact to transfer energy and momentum throughout the chain, to maximise the release velocities of the key joints, e.g. wrist and hand. Additionally, limited information is provided about the co-ordination strategies implemented to develop technique and have a positive impact on performance. Instead, a dynamic systems theory (DST) approach is recommended which will give more insight into the role underlying movement co-ordination patterns might play (Glazier and Robins 2011), and this is discussed in Cluster 2. Due to the relevance of both theories to this research it was decided that both deterministic model and a dynamic systems theory would be explored.

Table 3 2: Deterministic models - Cluster 1 (n = 3).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Chow & Mindock (1999)	RCT	Identify kinematics characteristics - classification & performance	n = 14 males (elite & emerging)- different classes; training camp	10 trials (2-3 min rest between trials) with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	Independent - Classification , performance Dependent - release characteristic s (vel, angle, height). Kinematics variables	*Descriptive stats for kinematic & temporal variables; *Pearson correlation for selected parameters & performance/clas sification	* Height, Angle, Vel at release; *angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	*Release speeds smaller than for able-bodied athletes a) angle & ang speed of upper arm at release b) range of motion of sh girdle, upper arm, forearm during fwd swing; c) av ang speed of sh girdle a), b), c) above - sig correlated with both classification & performance.	* Rel speed is a major determinant of the variation in performance & is highly correlated to classification. * Release angles similar to able-bodied athletes *Athletes (within same class) with better trunk mobility & control have advantage.	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis *Explore factors that have the greatest impact on performance
Chow, Chae, Crawford (2000)	RCT	Identify kinematics characteristics - classification & performance	n = 17 males (elite & emerging)- different classes; training camp	6 trials (2-3 min rest between trials) & best trial selected for analysis (between power & release).	2x VHS cameras (60 Hz); 13 body markers	Independent - Classification, performance Dependent - release characteristics (vel, angle, height). Kinematics variables	*Descriptive stats for kinematic & temporal variables; *Pearson correlation for selected parameters & performance/ classification	* Height, Angle, Vel at release; *angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	* Release angles & speeds smaller than for able-bod athletes a) Release height, b) upper arm ang speed at release, c) sh girdle range during delivery, trunk, sh girdle, d) upper arm av ang speed during delivery.	High average ang speed for each upper body segment during delivery required for optimal performance.	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis
Chow, Kuenster, Young-tae (2003)	RCT	Identify kinematics characteristics - classification & measured distance	n = 15 males (diff classes); tranining camp	6-10 trials with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	Independent - Classification, performance Dependent - release characteristics (vel, angle, height). Kinematics variables.	Mean (of 2 throws) used for Spearman Rank correl	* Height, Angle, Vel at release; *angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	* hand movement during the delivery is a major factor in JT performance. * Sig correls between Sh girdle angular speed at release & average sh angular speed during the delivery & class & performance.	* sh girdle motions not only differentiate the functional differences among wheelchair athletes but also play a role in determining the variation in performance * Release angles & speeds smaller than for able-bod athletes * shoulder girdle and trunk motions are significantly related to both the functional classification & performance *lack of trunk movement control in some subjects & sitting position may limit the trunk action during the delivery.	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis

Cluster 2: The role of biomechanics in Paralympic sport

There are a limited number (n = 3) of key reviews into biomechanical research into Paralympic sports (Table 3 3). An extensive review of multi Parasport related biomechanical research from a constraints-led approach highlighted the importance of the role that biomechanics should play in performance improvement (Keogh 2011). The challenge for those working with para athletes, such as coaches and biomechanists, is understanding the critical performance components that necessitate a high degree of invariance, as opposed to those that mostly utilise functional variability. Future biomechanical research is encouraged to closely link robust in-lab to applied field-based outcomes i.e. how coaches and athletes implement the research to improve performance (Morrien, Taylor and Hettinga 2016).

The constraints-led approach is discussed further within a systematic review on the kinematics of para throwing events (Keogh and Burkett 2012), whereby the use of a throwing frame (an organism-led component) for seated throwers is considered essential for performance. It supports earlier throwing frame specific research (Frossard, O'Riordan and Goodman 2010; Chung, Lin, Tor, Beyene and Garcia 2010; Grindle, Deluigi and LaFerrier 2012), both from a functional viewpoint assisting the athlete to be stable, enabling selection of the appropriate co-ordination strategy to maximally influence the release parameters, particularly release velocity (Keogh and Burkett 2012).

This constraints-led view relates to the dynamical systems theory (DST) which sees the athlete as a complex organism made up of numerous independent and interacting components working together to bring about the desired sporting movement. The co-ordination strategy that each athlete uses throughout the entire throwing movement to influence performance is of interest (Davids, Button and Bennett 2008). The DST is underpinned by the description of the interaction between three levels of constraints (environmental, task and organism) which influence the movement, how they might alter the co-ordination (control) strategy selected by the athlete, which ultimately affects performance (Davids, Button and Bennett 2008; Keogh 2011).

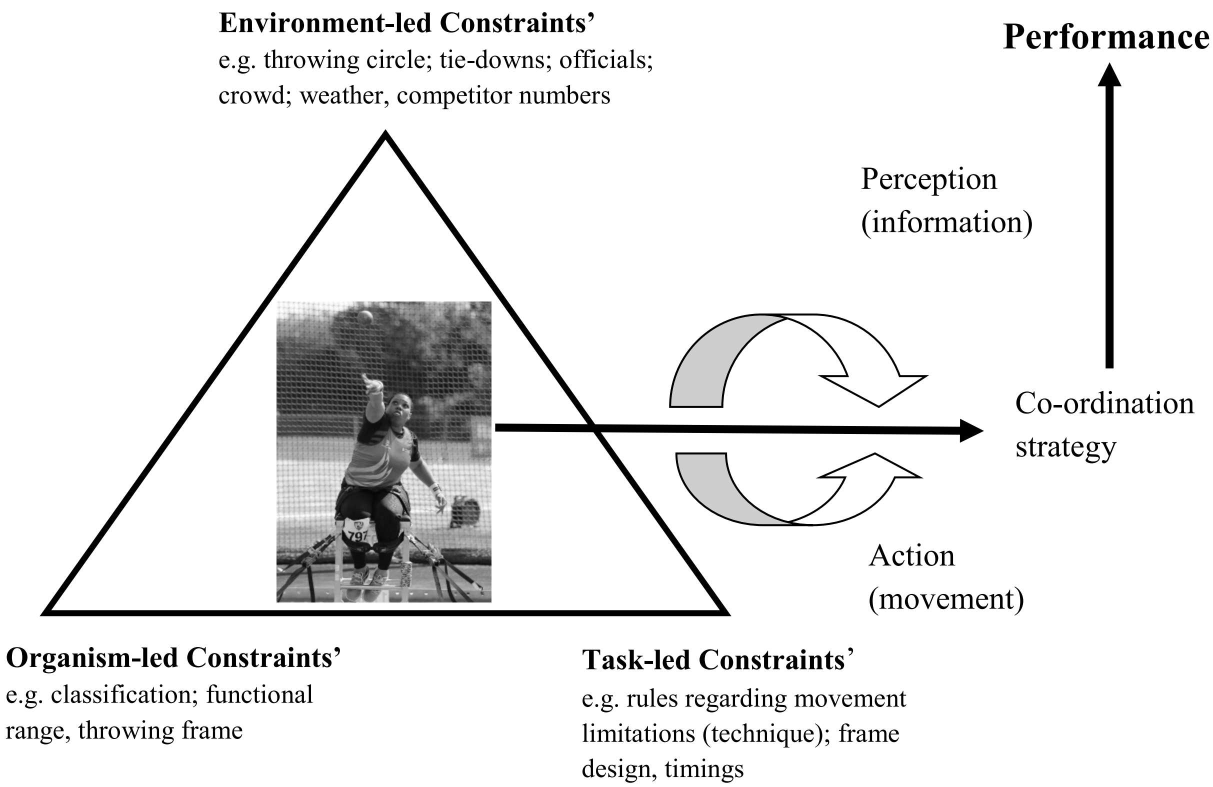


Figure 3 2: Adaption to Newell's (1986) model of interacting constraints' for seated shot-put, highlighting the effects on the variability to co-ordination strategy and performance (Davids, Glazier, Araujo and Bartlett 2003).

The three constraints levels described above have been applied to the seated shot-put environment based on Newell's (1986) model of interacting constraints, and is shown in Figure 3 2. The organisational-led constraints include the functional range between athletes in different classifications. Athletes within the same classification is also a consideration as impairment types and associated functional range can differ within each class. Having to use a piece of equipment i.e. a throwing frame is part of the rules of the event. The event organisation sees each athlete using a bespoke throwing frame to maximise their own function. The throwing frame is then secured in place for the athlete to use.

The environmental-led constraints include the nature of the throwing surface and how the throwing frame is fastened to the ground. This is an issue, even at Paralympic Games, with problems faced in competition whereby the throwing frame moves during movement as it is inadequately secured. Officiating and how the rules are interpreted by the officials have also proved problematic even at the major competitions. Inconsistent rule interpretation was a reason that the rules were changed in 2014. As all athletes are now required to throw from a seated position at all times, interpretation and uncertainty around throwing technique is reduced. Finally, the number of athletes participating in a seated shot-put event influences the time taken to complete the competition, with eight or more athletes taking over two hours to complete. This can influence performance as the order of throwing dictates how long an athlete waits on the field of play before they get the chance to throw.

Task-led constraints include the rules regarding permitted movement of the athlete. This has become more restrictive with rules since 2014 now stipulating that all athletes are seated in the same way throughout the throwing action. This then limits athletes to fully utilise all available function, thus providing another constraint. Additionally, the timings imposed on athletes as to how long they wait before getting onto their throwing frame and begin throwing, and how long they have to complete each throw are additional task-led constraints. Finally, throwing frame is also included within this constraint, as the rules of the event dictate its design. However, there is limited information available on throwing frame design and how it might influence functional movement.

Using a constraints-led approach of dynamical systems theory may also provide a theoretical basis through which athletes, coaches, applied practitioners and/or researchers can fully understand factors impacting on Paralympic sporting performance (Keogh and Burkett 2016). In seated throwing the varying athlete functional levels (an organism-led constraint) might suggest that the optimum co-ordination strategy between athletes may be very different, even within the same classification. This would be assumed even if the environment and task constraints were the same (Keogh 2011).

As seated throwers require a throwing frame to aid their movement, Keogh (2011) suggests that the organism-led constraint (the athlete's functional level) may emphasise the interaction between the athlete and their equipment (throwing frame). Throwing frame design then becomes critical as this has the potential to influence the organism-led constraints (functional level), which would lead to changes in the co-ordination strategy for maximum performance.

Table 3 3: The role of biomechanics in Paralympic sport - Cluster 2 (n = 3).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Keogh (2011)	Review	Highlight the role that biomechanics may play in performance improvement for summer Para sports		no details given	N/A	N/A	N/A	N/A	Challenge for coaches & biomechanists is to understand which components of performance are critical & require a high degree of invariance & which other aspects may effectively utilise functional variability.	Important to understand similarities & differences of Para/Olympic athletes to continual development of these athletes & to overall development of Para sports performance.	Extensive review of biomechanical research into some Para sports re constraints led approach to performance.	No information specific to para throwing.	
Keogh & Burkett (2012)	Systematic review	Provide a discussion on Para throwing for those using equipment	n=4 for Para seated throwing	Using EBSCO, PubMed & Google Scholar - terms used included Paralympic or disabled or disability; wheelchair or spinal cord injured or amputee; shot-put or javelin or discus	N/A	N/A	N/A	N/A	* Consistent with the constraints-led approach, specially designed throwing frames would appear an important component of the performance of para throwers (Chung et al., 2010), as they comprise part of the organism-level constraint & may provide the athletes with stability & sufficient freedom to rotate the trunk & upper limbs during the throws. * The subtle, but fundamental difference for the para athlete would appear to reflect the interaction of different levels of constraint under which movement is performed, in particular disability & its dependence on some form of equipment, e.g throwing frame	* Paralympic throwers are compromising their performance by utilizing lower release angles or if such 'optimal' angles are actually impossible to achieve due to the interaction of constraints that these athletes encounter in comp * Release angles are greater for lower classes suggesting that the optimum angle maybe influenced by a variety of organism-level contraints such as trunk control, muscular strength, power & range of movement. * Possible that certain aspects of throwing frame design may also alter preferred movement patterns & ranges of motion to the extend that lower release angles may actually become more optimal.	Extensive review of biomechanical research into Paralympic throwing & equipment use re constraints led approach to performance	* Limited no of research articles used * Focused on release angles rather than speeds as a measure of performance	* A better understanding of the relationship between the three levels of constraint (i.e. the human-machine interface & how this interacts with the environmental & task constraints) to achieve optimal performance while minimizing the risk of injury * More research needed to understand how improvements in inter-segment copordination patterns, particularly the ability to use the kinetic chain impacts on performance.

Morrien, Taylor, Hettinga (2016)	Systematic review	Provide an overview of biomechanical studies in Paralympic research & their relevance for performance in Paralympic sports.	n =34 studies, n=32 related to performance enhancement.	Using PubMed , search terms used included paralympic biomechanics , paralympic sport performance, paralympic athlete performance, & paralympic athlete.	N/A	N/A	N/A	N/A	N/A	* Biomechanical research is important for performance by gaining insight into technical optimization, injury prevention, and evidence-based classification in Paralympic sports. * Future studies should include physiological and biomechanical measures, allowing the assessment of the capability of the human body, as well as the resulting movement.	Extensive review of biomechanical research into Paralympic sports	* Future studies are advised to focus on physiological & biomechanical principles to be able to better elucidate performance and performance enhancement. * Future research is encouraged to continue to link the well-controlled laboratory outcomes to valid field-based outcomes.

Although shot-put is a closed skill and potentially more so for seated athletes, the environment, and other circumstances (such as official intervention and/or equipment malfunction) could be inconsistent. Skilled athletes are usually able to adapt to these changing circumstances leading to differences in movement variability (Wagner, Pfusterschmied, Klous, von Duvillar and Muller 2012).

Keogh and Burkett (2012) conclude that seated throws research to date consistently show lower angles of release, (as well as lower release velocities) for seated shot-putters compared to their standing counterparts, and it would appear that seated throwers may be compromising their performance by this. However, it might not be appropriate to make this comparison as it may be impossible for seated shot-putters to actually achieve the values displayed by standing throwers due to the constraints on seated throwing technique, throwing frame and other competition related constraints. Research involving the release variables for seated throwing will be discussed in Cluster 4.

Cluster 3: 3D capture and analysis

Of the 26 articles identified for this literature review only four of them utilised 3D capture and analysis as shown in Table 3 4. The research of Frossard, O'Riordan and Goodman (2005) attempted to address the dynamic nature of seated discus by studying the main environments that were relevant and could assist improve performance of elite seated throwing athletes (in- training, in-lab and in-competition). The in-lab testing involved a 12 camera Vicon 3D recording system, with the participants throwing from a specifically designed adjustable throwing frame (Figure 3 3). Kinematic data was collected, which will be discussed within Cluster 5.

Additionally, loading profiles of the three points where the athlete was in contact with the throwing frame (both feet and back of knee) during the throwing action were generated. The magnitude of contact points loading at release was also determined. Athlete positioning in relation to the throwing frame complied with the IPC rules at the time (pre 2008), as detailed in Table 2 2, so is only partially relevant to current rules. The in-lab testing contributes to the small amount of published research on the 3D segmental analysis of seated throwers (discus in this instance) that would allow for favourable release conditions to be achieved.

Table 3 4: Research involving 3D capture and analysis - Cluster 3 (n = 4).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Frossard, O'Riordan, Goodman (2005)	Descriptive	Present the innovations & dynamic research procedure of an integrated approach based on applied research, as implemented by a MDT.	n=2 male Elite F34 athletes	**In Lab** 3x testing sessions focussing on foot placement; Anthrop measures taken; 10 throws in 5 diff feet positions (lots of rest);	1x Kister force plate (1080 Hz)-total external forces & moments; 2x load cells (100Hz)-forces under each foot; 2x Redlake highspeed camera (150Hz)-point of release; 12x Vicon cameras (120Hz)-3D coordinates.	N/A	N/A	Performance level of athletes improved as a result of testing & evidence based provision of information.	Loading profile at 3 pts of contact (2x feet+back of knee) - Magnitude of load at contact pts on release important; Range of movement, linear & ang velocity & momentum & CoM of each segment; Release parameters of discus.	Evidence based approach (1) Improves modelling & performance prediction; (2) Informs athletes & coaches of technique relating to frame design;	Throwing frame design - a fully adjustable frame was made for the research	limited subject no	More In Lab testing in association with In Comp capture
Tweedy, Connick, Burkett, Sayers, Meyer, Vanlandewijck (2012)	RCT	To establish 2 standardized throwing frame configurations (self-selected) for overhand seated throwing, with/without holding pole. Does hand speed at release facilitate perf for pole vs no pole conditions?	n=47 (non-disabled) males (21.9+ 2.6 yrs)	3 testing sessions (48hr recovery between); **1st session** - pole & no-pole for subjs to self select preferred seated condition- Seat angle/ backrest height/ pole posn **2nd session** - with pole in preferred seated condition; **3rd session** - no pole in preferred seated condition.	AUS (n=29) subjs - 3D 6 camera QSM (150 Hz); 32 relective markers EURO (n=18) subjs - 1x Basler video camers (100Hz)	Independent: Pole vs no-pole; Dependent: Hand release speed Control: throwing frame	A paired sample t-test was used to evaluate differences in hand speed between pole & no pole conditions.	Primary outcome: HAND speed at RELEASE for pole vs no pole conditions.	Results from this study do not indicate whether it is more advantageous to throw with or without a pole.	*Established the seated throwing configurations preferred by non- disabled people, providing a valid guide for researchers wishing to evaluate the impact of impairment on seated throwing performance independent of throwing frame configuration. *Results do not indicate whether it is more advantageous to throw with or without a pole.	Large subject no; standardised throwing frame	*non-disabled subjects; *inexperienced at seated throwing (although familiarisation given); *overhead ball throwing not a seated throws event;	Comparison to disabled subjects particulary seated throwers

Lee, Davis, Judge, Kwon, Han, Kim et al. (2015)		Analyse the release parameters of seated shot putters at US trials & how each affects performance	n=16 (11M + 5F), F53-58	48 trials from 16 athletes = 3 trials per athlete	4 digital cameras (60Hz); 16 body points, Kwon 3D & Matlab	* Independent: Release angle, speed, height; * Dependent: Performance * Independent: Gender & Class; * Dependent: Release angle, speed, height & performance.	*Multiple regression between release parameters & performance *2-way Factorial MANOVA between subjects (gender & class) & release parameters & performance.	Gender differences between release parameters & performance.	Release speed & angle - sig correlation to performance.	* Focus training on generating speed at release with consistent release angle (as close to 37degs as poss) * Throwing with a high release speed is more important to performance than throwing at the optimum release angle	Elite athletes, large subject no, recorded in comp	Reduced capture rate; Reduced no of body points; Rules have changed since capture.	Compare in-comp with in-lab capture with higher capture rate; Recapture using new rules
Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx, Tweedy (2016)	RCT	Identify/compare performance related kinematics variables	n=29 (non-disabled) males (21.9±2.6 yrs)	Single session; 12 (6+6) max OH throws with 1kg ball; Subjs self selected seating configuration;	3D 6 camera QSM (150 Hz); 31 relective markers	Independent: Pole vs no-pole; Dependent: ball release speed; Control: throwing frame	*Descriptive stats for kinematic & temporal variables; *One-way ANOVA for pole vs no-pole; *Pearson correlation for each variable & ball speed at release	temporal measures; kinematic measures	*No sig diff in release speeds between conditions; *with pole - higher shoulder ang vel during arm accel & ball release phases.	* With pole - changed throwing tech with sig diffs for 8 kinematics variables * With pole - Max shoulder internal rotation most influence on ball speed - also a key component in standing throwing * Other variables known to contribute in standing throwing e.g. trunk tilt & upper trunk rotation - no correlation to performance in seated position.	Large subject no; standardised throwing frame.	*non-disabled subjects; *inexperienced at seated throwing (although familiarisation given); *trial sequence not randomised.	Comparison to disabled subjects & experienced seated throwers

The studies of Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck (2012) and Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy (2016) conducted three testing sessions involving 47 non-disabled male participants. Tri-dimensional data was captured using a six-camera set-up (150Hz) of three maximal overhead ball throws from self-selected positions, with and without a holding pole. The self-selection of seating position in terms of seat angle, back rest height and holding pole, was enabled using an adjustable throwing frame (Figure 3 4). Release and kinematic variables were analysed which will be discussed within Clusters 3 and 4 respectively.

Recommendations were provided on aspects referring to sitting direction and holding pole use and their impact on performance. However, by using non-disabled participants and the overhead throw (not included in the Paralympic programme), the relevance for para athlete technical improvement maybe limited. Additionally, the testing environment was in-lab where participants would not be able to throw for distance due to lack of space. An artificial throwing frame that could not be used in competition was also utilised. Thus, the application for elite athletes wanting to improve performance is reduced.

Another study (Lee, Davis, Judge, Kwon, Han, Kim et al. 2015) conducted during national trials competition, involved data capture using four digital cameras (60 Hz) of 16 athletes (11 male and five female) across classes F53-58 throwing three shot-put trials each. The aim was to analyse the release parameters and their impact on performance (distance thrown) with 3D analysis across the delivery phase (known as the completion phase for this thesis as shown in Figure 2 2). The release variables determined will be discussed later within Cluster 3. A comparison of this in-competition data with lab-based capture utilising a more extensive camera set-up and higher capture rates would further improve the research. As with the other research involving 3D capture and analysis, older rules were in force at the time of this study and so this needs to be considered when reviewing the results.

Only 16% of the available seated throwing research involved 3D capture and analysis. A likely reason for the lack of biomechanical information might be because of the complexity of accessing large numbers of seated throwers with consistent throwing technique. Due to the technical nature of the shot-put event 3D capture is essential for kinematic analysis, and advanced data analysis is needed to fully understand the complex nature of sporting activity (Yu, Broker and Silvester 2002). This is particularly relevant to seated throwing and is of important when establishing the relationship of athlete technique with the throwing frame. It is anticipated that this thesis will include 3D capture and analysis using a system involving more cameras than the research included and detailed in Table 3 4.

Cluster 4: Release variables

There were six articles that involved release variables of seated throwers, as shown in Table 3 5. The earliest research focused on the parameters of the throwing implement's trajectory (Chow and Mindock 1999; Chow, Chae and Crawford 2000; Chow, Kuenster and Young-tae 2003). It included three out of four of the events available to seated throwers i.e. discus, shot-put and javelin. Despite criticisms from Glazier and Robins (2011), as discussed previously, results from these studies were important, as they were the first to set the scene.

During a training camp, between 10 - 17 male seated throwers (emerging and elite), across a variety of classifications were tested. For the study focusing on seated shot-put (Chow, Chae and Crawford 2000), six trials per athlete (n = 17) were captured using two dimensional cameras. Outcome measures focused on the release parameters (velocity, angle and height). Additionally, angle and angular velocities at release for key joints were also considered, and these will be discussed in Cluster 5. The best performance for each athlete i.e. the trial producing the longest distance thrown, was used for analysis purposes. The movement phase that was utilised was that of the completion phase, from the power to release positions (Figure 2 3).

The lower release variables for seated shot-putters were compared to standing athletes. For example, velocity of release for seated athletes was 5.3 – 7.8 ms^{-1} (with increasing function) compared to 13.2 ms^{-1} (McCoy, Gregor, Whiting, Rich and Ward 1984), 11.4 ms^{-1} (Dessureault 1978) and 10.6 ms^{-1} (Alexander, Lindner and Whalen 1996). Similarly, angles of release were less for the seated athletes, 21.2 – 34.3 degs (with increased function) compared to 37.2 degs (Alexander, Lindner and Whalen 1996), 36.8 degs (Dessureault 1978) and 36.3 degs (McCoy, Gregor, Whiting, Rich and Ward 1984). It should also be noted that the IPC classification system has been updated from the time that Chow and his colleagues conducted their research so placing additional limitations on their results.

Table 3 5: Research focusing on release variables - Cluster 4 (n = 9).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Chow & Mindock (1999)	RCT	Identify kinematics characteristics - classification & performance	n = 14 males (elite & emerging)- different classes; training camp	10 trials (2-3 min rest between trials) with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	Independent - Classification, performance Dependent - Kinematics variables	*Descriptive stats for kinematic & temporal variables; *Pearson correlation for selected parameters & performance/ classification	*angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	a) angle & ang speed of upper arm at release b) range of motion of sh girdle, upper arm, forearm during fwd swing; c) av ang speed of sh girdle a), b), c) above - sig correlated with both classification & performance.	*Athletes (within same class) with better trunk mobility & control have advantage	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	*Data collection from major champs; *3D data analysis *Explore factors that have the greatest effect on performance
Chow, Chae, Crawford (2000)	RCT	Identify kinematics characteristics - classification & performance	n = 17 males (elite & emerging)- different classes; training camp		2x VHS cameras (60 Hz); 13 body markers	Independent: Classification, performance Dependent: Kinematics variables	*Spearman rank order correl coeffs for selected parameters & performance/ classification.	* Height, Angle, Vel at release;	a) Release height, b) sh girdle range during delivery, trunk, sh girdle, a), b) above - sig correlated with both classification & performance.		*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model.	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis

Chow, Kuenster, Young-tae (2003)	RCT	Identify kinematics characteristics - classification & measured distance	n = 15 males (diff classes); tranining camp	6-10 trials with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	* Independent: Classification, performance; * Dependent: release characteristics (vel, angle, height).	Mean (of 2 throws) used for Spearman Rank correl	*angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	* hand movement during the delivery is a major factor in JT performance. * Sig correls between Sh girdle angular speed at release & average sh angular speed during the delivery & class & performance.	* sh girdle motions not only differentiate the functional differences among wheelchair athletes but also play a role in determining the variation in performance, * shoulder girdle and trunk motions are significantly related to both the functional classification & performance, *lack of trunk movement control in some subjects & sitting position may limit the trunk action during the delivery.	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis
Frossard, O'Riordan, Goodman (2005c)	Descriptive		n=12 male Elite F33/34 discus throwers at 2002 WCs	**In Comp:** Video footage of all athletes competing in F33/34 discus comp	2x digital cameras (50Hz); front on & side on as close to throwing plate as possible; syncronised using Dartfish	N/A	N/A	Performance against resultant, vertical, a-p & m-l components of back & front feet positions	*2D coords of heel, top of foot, ankle of both feet tracked frame by frame; *Qualititive analysis of performance against; (1) no of Lfoot, Rfoot, knee, buttock, arm-	No definite link between feet position & performance; Feet position is related to functional level & physical ability	3 x Testing environments including during training, in lab & during competition	2D only; No reflective markers used;	More in-comp capture & analysis
Frossard, Smeathers, O'Riordan (2007)	Descriptive	n=7 (gold medallists) - Top 4 male & Top 3 Female	Determine the mag of differences across classes & genders for shot trajectory parameters.	Best attempt (perf) used for analysis; Analysis with Silicon Coach (50Hz)	1x Digital camera; 25 Hz; 1.10m high; 8-10m perp to throw	*Independent : Classification; gender * Dependent: release characteristics (vel, angle, pt)		Release parameters (vel, ang, pt of release)	*Release vel ↑ with perf & classification for M & F; *Release ang ↑ with perf & classification for M & F; *Release pt ↑(weaker) with perf & classification for M & F	* The velocity and angle seem to be the two predominant factors determining the performance of gold medalists. * It is likely that the performance relied more importantly, however, on the throwing technique & functional outcome as they are both directly related to velocity & angle of release.	Data collected during WC events - 2000 PGs, 2002 WCs	Only 1 camera used	3D analysis will ↑accuracy of vel & angular data

Frossard, O'Riordan, Goodman (2009a) Frossard, O'Riordan, Goodman (2009b) Frossard, O'Riordan, Goodman (2009c)	Descriptive	Provide coaches, athletes, sports scientists & classifiers true determinants of perf including (1) Release parameters (2) sequencing of actions prior to release (3) throwing frame design.	n=103 (77M & 26F) with 600 attempts across 10 classes (F33, 34, F52-58) from 14 events (10xSP, 3xDT, 1xJT)	From 2006 IPC WCs. Performances taken from official result sheets	2x digital cameras (50Hz); front on & side on; syncronised using Dartfish	Independent - Classification; gender Dependent - performance (m)	**Inter-Class Analysis** *Perf distribution in relation to:Class-to-Class & Gender-to-Gender; Class-to-Group of disability distribution; **Intra-Class Analysis** *Perf data - Ranking, Attempt, Order, Other; Descriptive perf stats - no of athletes & throws, mean, SD, COV, Min, Max, Range; Distribution of perf.	Improve understanding for Evidence based classification & research. Facilitate training methods. Inform of interaction between technique & frame design.		World first of evidence based data gathering & information dissemination in the form of open access ebooks	Rules relating to seated throwing & classification have been updated since this data collection	Evidence based data gathering from each major champs with current rules.	Evidence based data gathering from each major champs with current rules.
Lee, Davis, Judge, Kwon, Han, Kim et al. (2015)		Analyse the release parameters of seated shot putters at US trials & how each affects performance	n=16 (11M + 5F), F53-58	48 trials from 16 athletes = 3 trials per athlete	4 digital cameras (60Hz); 16 body points, Kwon 3D & Matlab	* Independent: Release angle, speed, height; * Dependent: Performance * Independent: Gender & Class; * Dependent: Release angle, speed, height & performance.	*Multiple regression between release parameters & performance *2-way Factorial MANOVA between subjects (gender & class) & release parameters & performance.	Gender differences between release parameters & performance.	Release speed & angle - sig correlation to performance.	* Focus training on generating speed at release with consistent release angle (as close to 37degs as poss) * Throwing with a high release speed is more important to performance than throwing at the optimum release angle	Elite athletes, large subject no, recorded in comp	Reduced capture rate; Reduced no of body points; Rules have changed since capture.	Compare in-comp with in-lab capture with higher capture rate; Recapture using new rules

Later, a descriptive study focused on the release parameters of Gold medallist seated shot-putters at World Class competitions including the 2000 Paralympic Games and 2002 IPC World Championships (Frossard, Smeathers and O'Riordan 2007). This study analysed the performances of male and female shot-putters (classes F52-55), with a view to improve the understanding of the release parameters of elite seated shot-putters. Similarly, to Chow, Chae and Crawford (2000) only the best performance (i.e. longest distance thrown) by each of the athletes claiming the gold medal in each class was analysed. Both release velocity and angle were found to be predictors of better performance.

Although the release velocities (8.30 – 9.96 ms^{-1}) and angles (27.54 – 32.47 degs) for male athletes (with increasing function and performance) were higher than those reported by Chow, Chae and Crawford (2000), they were still lower than those by standing athletes, as reported above. Nevertheless, these higher release parameters specific to seated shot-putters, may expose some differences between analysing performance whilst training as opposed to during major competition. This was one of the recommendations for future research stipulated by Chow and his colleagues, as a consequence of their findings. Additionally, the video capture involved the use of a single camera and relatively low capture rate (25 Hz) because of environmental constraints due to filming at major championships. This would likely increase error.

The most extensive descriptive research into seated throwing included 2D video capture (50 Hz) of 103 athletes (77 male and 26 female) including 600 attempts across 10 classes (F33, F34, F52-58) across seated shot-put, discus and javelin events at the 2006 IPC World Championships (Frossard, O'Riordan and Goodman 2009). One intention was to identify the release variables that might influence performance. However, the research mostly focused on classification and gender with the view to improve the understanding of evidenced based classification between genders. By describing characteristics of the throwing frames, it also informed the interaction between throwing technique and frame design.

Another study (Lee, Davis, Judge, Kwon, Han, Kim et al. 2015), this time conducted during national trials competition, involved data capture using four digital cameras (60 Hz) of 16 athletes (11 male and five female) across classes F53-58 throwing three shot-put trials each. The aim was to analyse the release parameters and their impact on performance (distance thrown) with 3D analysis across the delivery (completion) phase. Release speed was highlighted as the best predictor of performance across both genders. Recommendations from the research included directing training on generating release speed with consistent release angles (as close to 37 degs as possible).

This is consistent with earlier research with standing shot-putters (Dessureault 1978; McCoy, Gregor, Whiting, Rich and Ward 1984; Alexander, Lindner and Whalen 1996). It also consolidates findings from standing shot-put literature where release velocity is reported as being the main predictor of better performance (Young 2001; Young and Li 2005; Zi, Dapena and Bingham 2009). A comparison of this in-competition data with in-lab capture utilising a more extensive camera set-up and higher capture rates would further improve the research.

Conducting research during competition is considered a strength, as constraints determining performance can differ dramatically between training and real competition, particularly at major championships (Keogh 2011; Churton and Keogh 2013; Keogh and Burkett 2016). This was further confirmed by Chow, Chae and Crawford (2000) who found that performances were 15% lower in training than in competition. Any future research focusing on performances in-training and in-competition will enhance the depth of work into the biomechanics of seated throwing.

Cluster 5: Kinematic analysis

There were seven articles involving kinematic analyses associated with seated throwing, and full details are shown in Table 3 6. Chow, Chae and Crawford (2000) in their article focusing on seated shot-put looked at angle and angular velocities at release for key joints (trunk, shoulder girdle, upper arm, forearm and hand) and their relationship to both athlete function (classification) and performance. They found significant correlations to classification and performance for shoulder girdle and trunk range.

A later study presented an innovative, dynamic and integrated approach to applied research using a multi-disciplinary team incorporating athletes, coaches, biomechanists and engineers (Frossard, O'Riordan and Goodman 2005). It involved working with elite Australian athletes (n = 2 in F34 class) and coaches to improve performance. Testing took place under three different conditions: during training, in a biomechanics lab and during major competition (in-training, in-lab, and in-competition). Foot positioning of seated discus was the focus of this particular study, with seven training sessions recorded with five different feet positions trialled using a specially designed fully adjustable throwing frame manufactured by engineers (Figure 3 3). Segmental angles of the lower limbs in the sagittal plane and the movement pathway of the hips and upper limbs were determined and tracked throughout the training using 2D filming and analysis.

Finally, at the 2002 IPC World Championships, video footage was captured of 12 male elite F33/34 discus throwers using the quality control procedure that will be described in Cluster 6 (Frossard, O'Riordan and Goodman 2005; O'Riordan and Frossard 2006). The purpose was to see if feet position influenced performance positively during major competition, Despite showing there was no definite link, it is likely that it is related to functional level and physical ability. However, performances improved for the Australian seated discus throwers after their favourable feet position was determined as part of the in-training and in-lab testing and interventions.

For the studies of Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck (2012) and Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy (2016), the aims were to identify and compare performance-related kinematic variables related to seated overhead throwing with and without the use of a holding pole. The results did show significant differences for eight of the kinematic variables focused on and release ball speed. The most influential variable was maximum shoulder internal rotation when using the holding pole. However, the results did not show whether there was any advantage to using a holding pole for hand speed at release. Interestingly, there was no correlation with upper trunk rotation and trunk tilt to seated throwing performance. This is in contrast to research into other throwing and striking activities, such as shot-put, baseball and golf, for standing athletes, which showed that trunk angular acceleration plays a significant role in technique to influence performance (Hirashima, Kadota, Sakurai, Kudo and Ohtsuki 2002; Joyce, Burnett, Ball and Ball 2010).

The works of Tweedy et al. (2012) and Burkett et al. (2016) are more likely to guide future research evaluating the impact of impairment on seated throwing performance, independently of throwing frame configuration. Despite the large participant number and a standardised throwing frame utilised within this research, there were several limitations. These included the inclusion of non-disabled participants who were inexperienced at throwing from a seated position. Additionally, overhead ball throwing is not a seated throwing event or comparable to the shot-putting action. However, despite their research taking place before the latest 2014 rule change, they did conduct the testing using a seating position that is largely now part of the current rules. There is the opportunity for a comparative study to repeat the research protocol with experienced disabled seated throwers in one of the identified Paralympic throwing events.

The most recent research is by Abdelkader, Madani and Bouabdellah (2020) who investigated some kinematic variables of one elite seated shot-putter in Class F33. Two digital cameras situated parallel to the throwing side of the athlete were used, one in line with the release position and the other 5.5m ahead to capture the flight of the shot-put. Kinovea, a freely available analysis software package was utilised for the data analysis.

Kinematic variables considered were largely temporal from the start to the release positions. Some joint angles were also included at the same two positions and there were no velocity variables considered. Using the movement pattern terminology created for this research, results from this case study showed correlations to performance for the release gain, wrist angle at 1st preparation position, height of shot-put along with a decrease in release angle at the power position.

It was a case study involving one athlete only, conducted using 2D digital cameras and less robust analyses software. These are limitations however it is currently the only research conducted using elite athletes and under the current rules. Research involving the current rules is likely to be more specific and relevant to current coaches and athletes looking to include technical interventions to improve performance.

Table 3 6: Research focusing on kinematic analysis – Cluster 5 (n = 9).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Chow & Mindock (1999)	RCT	Identify kinematics characteristics - classification & performance	n = 14 males (elite & emerging)- different classes; training camp	10 trials (2-3 min rest between trials) with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	Independent: Classification, performance Dependent: Kinematics variables	*Descriptive stats for kinematic & temporal variables; *Pearson correlation for selected parameters & performance/ classification	*angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	a) angle & ang speed of upper arm at release b) range of motion of sh girdle, upper arm, forearm during fwd swing; c) av ang speed of sh girdle a), b), c) above - sig correlated with both classification & performance.	*Athletes (within same class) with better trunk mobility & control have advantage	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model.	*Cameras not synchronised *Manual digitising *Limited resolution	*Data collection from major champs; *3D data analysis *Explore factors that have the greatest effect on performance
Chow, Chae, Crawford (2000)	RCT	Identify kinematics characteristics - classification & performance	n = 17 males (elite & emerging)- different classes; training camp		2x VHS cameras (60 Hz); 13 body markers	* Independent: Classification, performance; * Dependent: release characteristics (vel, angle, height).	*Spearman rank order correl coeffs for selected parameters & performance/ classification.	* Height, Angle, Vel at release;	a) Release height, b) sh girdle range during delivery, trunk, sh girdle, a), b) above - sig correlated with both classification & performance.		*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model.	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis
Chow, Kuenster, Young_tae (2003)	RCT	Identify kinematics characteristics - classification & measured distance	n = 15 males (diff classes); tranining camp	6-10 trials with 2 best throws used for analysis	2x VHS cameras (60 Hz); 13 body markers	Independent - Classification, performance Dependent - Kinematics variables	Mean (of 2 throws) used for Spearman Rank correl	*angle & ang speeds at release for trunk, shoulder girdle, upper arm, forearm, hand	* hand movement during the delivery is a major factor in JT performance. * Sig correls between Sh girdle angular speed at release & average sh angular speed during the delivery & class & performance.	* sh girdle motions not only differentiate the functional differences among wheelchair athletes but also play a role in determining the variation in performance, * shoulder girdle and trunk motions are significantly related to both the functional classification & performance, *lack of trunk movement control in some subjects & sitting position may limit the trunk action during the delivery.	*First research in this area, large subj no of disabled athletes *Provides detailed deterministic model	*Cameras not synchronised *Manual digitising *Limited resolution	Data collection from major champs; 3D data analysis

Frossard, O'Riordan, Goodman (2005a)	Descriptive	Describe the procedure, outcomes & limitations of the conventional approach, based on fundamental research	n=3 male Elite F34 athletes	**During training** *7 testing sessions in total - 7sec recording duration (as above) *Caibration frame used; Different foot positions trialled	2x digital cameras (50Hz); front on & side on; syncronised using Dartfish	N/A	N/A	Informed parameters for **In Lab** & **In Comp** testing - (1) 5 key feet positions; (2) parameters to extract from video recording during real-events	Segmental angles of lower limbs in sagittal plane; Movement pathway of Hip & upper limbs		MDT assembly including coaches, athletes, biomechanists, engineers	2D only - does not allow for motion in transverse plane; reflective markers used; No kinetic data; limited subject no	Using more cameras
Frossard, O'Riordan, Goodman (2005b)	Descriptive	present the innovations & dynamic research procedure of an integrated approach based on applied research, as implemented by a MDT	n=2 male Elite F34 athletes	**In Lab** *3 testing sessions focussing on foot placement; *Anthrop measures taken; *10 throws in 5 diff feet positions (lots of rest);	1x Kister force plate (1080 Hz)-total external forces & moments; 2x load cells (100Hz)-forces under each foot; 2x Redlake highspeed camera (150Hz)-point of release; 12x Vicon cameras (120Hz)-3D coordinates	N/A	N/A	Performance level of athletes improved as a result of testing & evidence based provision of information	Loading profile at 3 pts of contact (2x feet+back of knee) - Magnitude of load at contact pts on release important; Range of movement, linear & ang velocity & momentum & CoM of each segment; Release parameters of discus	Evidence based approach - (1) Improves modelling & performance prediction; (2) Informs athletes & coaches of technique relating to frame design;	Throwing frame design - an fully adjustable frame was made for the research	limited subject	More In Lab testing in association with In Comp capture
Frossard, O'Riordan, Goodman (2005c)	Descriptive		n=12 male Elite F33/34 discus throwers at 2002 WCs	**In Competition** Video footage of all athletes competing in F33/34 discus competition	2x digital cameras (50Hz); front on & side on as close to throwing plate as possible; syncronised using Dartfish	N/A	N/A	Performance against resultant, vertical, a-p & m-l components of back & front feet positions	*2D coords of heel, top of foot, ankle of both feet tracked frame by frame; *Qualititive analysis of performance against; (1) no of Lfoot, Rfoot, knee, buttock, arm-rest (2) type of contact (strapped, locked, tucked) (3) Foot position (distance & angle)	No definite link between feet position & performance; Feet position is related to functional level & physical ability	1 environment of 3 including during training, in lab & during competition	2D only; No reflective markers used;	More in Comp capture & analysis

Tweedy, Connick, Burkett, Sayers, Meyer, Vanlandewijck (2012)	RCT	To establish 2 standardized throwing frame configurations (self-selected) for overhand seated throwing, with/without holding pole. Does hand speed at release facilitate perf for pole vs no pole conditions?	n=47 (non-disabled) males (21.9+ 2.6 yrs)	3 testing sessions (48hr recovery between); **1st session** - pole & no-pole for subjs to self select preferred seated condition- Seat angle/ backrest height/ pole posn **2nd session** - with pole in preferred seated condition; **3rd session** - no pole in preferred seated condition.	AUS (n=29) subjs - 3D 6 camera QSM (150 Hz); 32 relective markers EURO (n=18) subjs - 1x Basler video camers (100Hz)	Independent: Pole vs no-pole; Dependent: Hand release speed Control: throwing frame	A paired sample t-test was used to evaluate differences in hand speed between pole & no pole conditions.	Primary outcome: HAND speed at RELEASE for pole vs no pole conditions.	Results from this study do not indicate whether it is more advantageous to throw with or without a pole.	*Established the seated throwing configurations preferred by non- disabled people, providing a valid guide for researchers wishing to evaluate the impact of impairment on seated throwing performance independent of throwing frame configuration. *Results do not indicate whether it is more advantageous to throw with or without a pole.	Large subject no; standardised throwing frame	*non-disabled subjects; *inexperienced at seated throwing (although familiarisation given); *overhead ball throwing not a seated throws event;	Comparison to disabled subjects particulary seated throwers
Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx, Tweedy (2016)	RCT	Identify/compare performance related kinematics variables	n=29 (non-disabled) males (21.9±2.6 yrs)	Single session; 12 (6+6) max OH throws with 1kg ball; Subjs self selected seating configuration;	3D 6 camera QSM (150 Hz); 31 relective markers	Independent: Pole vs no-pole; Dependent: ball release speed; Control: throwing frame	*Descriptive stats for kinematic & temporal variables; *One-way ANOVA for pole vs no-pole; *Pearson correlation for each variable & ball speed at release	temporal measures; kinematic measures	*No sig diff in release speeds between conditions; *with pole - higher shoulder ang vel during arm accel & ball release phases.	* With pole - changed throwing tech with sig diffs for 8 kinematics variables * With pole - Max shoulder internal rotation most influence on ball speed - also a key component in standing throwing * Other variables known to contribute in standing throwing e.g. trunk tilt & upper trunk rotation - no correlation to performance in seated position.	Large subject no; standardised throwing frame.	*non-disabled subjects; *inexperienced at seated throwing (although familiarisation given); *trial sequence not randomised.	Comparison to disabled subjects & experienced seated throwers
Abdelkader, Madani, Bouabdellah (2020)	Case study	Kinematic variables analysis of shot-put activity in para-athletics (class F32/33) and their relationships with the digital level achievement.	n=1 (F33 male Gold medallist); (37 yrs)	8 trials) captured in single testing session - with 6 best trials analysed	2x digital cameras (720p video resolutation); both cameras side on to throwing circle (Camera 1- 1.5m ahead of circle midline; Camera 2 - 5.5m ahead of front edge of circle); Analysis via Kineovea	Dependent - Performance; Independent - Kinematics at start and release.	Descriptive; Pearson's Correlation		correlations to performance for; *release gain and wrist angle at 1st preparation position, *height of shot-put and a decrease in release angle at the power position.	An understaning of kinematics is important for Paralmpic athletes	none detailed	none detailed	Greater number of athletes from varied classes

Cluster 6: Throwing frame related

There are a number of throwing frame related research (n = 9), with full details presented in Table 3 7. They tend to take two lines of thought with some focused on describing the throwing frame characteristics that were being used by elite athletes in major competitions. Others focus on the design of uniform adjustable throwing frames that could be used by all athletes. Since athletes usually use their own throwing frames in competition (Frossard, O'Riordan and Goodman 2005), the setting up for each athlete can be time consuming, with international competitions lasting in excess of two hours (if eight or more athletes are competing in the event). It is anticipated that a uniform throwing frame might minimise the set-up time but would also need to be suitable for athletes in all classifications.

Information regarding throwing frame characteristics was captured during the 2006 IPC World Championships (Frossard, O'Riordan and Goodman 2009a, b, c; Frossard, O'Riordan and Goodman 2010). The characteristics included the number and type of contact points between the athlete and the throwing frame, body and throwing frame orientation, seating arrangement and nature of attachment for feet and legs. The intention was to present a catalogue of throwing frame characteristics used by elite male seated shot-putters, including whole body, lower and upper limb related features. The profiles developed from world's best athletes displayed the frequency of characteristics and the raw data provided key benchmark information for throwing frame design and the coaching of seated throwing. There was also the potential to influence classification and officiating (Table 3 6). It consolidated the earlier work focusing on seated discus throwers (Frossard, O'Riordan and Goodman 2005; Frossard, O'Riordan and Smeathers 2012a and 2012b). The information was further developed to provide e-books for those involved in the coaching, officiating and classification of seated throwers (Frossard, O'Riordan and Goodman 2009a, b and c).

This longitudinal body of work by Frossard and colleagues, included data capture over an eight-year period at three Paralympic Games and two IPC World Championships. It contributed significantly to the understanding of the seated throwing technique, throwing frame design and their importance and relationship to performance, during this time. These studies also contributed to methodology considerations for the recording of kinematic data during competitions. All of the studies were conducted using rules that have been updated (Table 2 2), so is a limitation and thus the information is only partially relevant to coaches and athletes currently training to improve performance.

The interpretation of the results should be considered within the context at the time, with regards to previous rules. However, they do provide guidelines for similar longitudinal studies to be conducted under current rules, particularly relating to changes in technique and performance, and the impact on classification that have come about as a result of rule changes and throwing frame design constraints. Thus, it becomes important to consider more recent publications. i.e. post the 2014 rule change.

There has been limited publications specifically on throwing frame design (n = 4), as shown in Table 3 7. An adjustable throwing frame was constructed mostly for research purposes. However, since it was designed according to the event rules at the time, it was later used in national and international competitions (Figure 3 3). The design characteristics for this particular throwing frame have not been published formally in their own right. However, its design and functionality allowed for multiple athletes as well as enabling force plates to be added so kinetic data could be captured. It was used for a number of data collection situations including the research to determine the favourable feet position for seated discus throwers using both dynamic and kinematic data collection (Frossard, O'Riordan and Goodman 2005; Frossard, O'Riordan and Smeathers 2012a and 2012b).

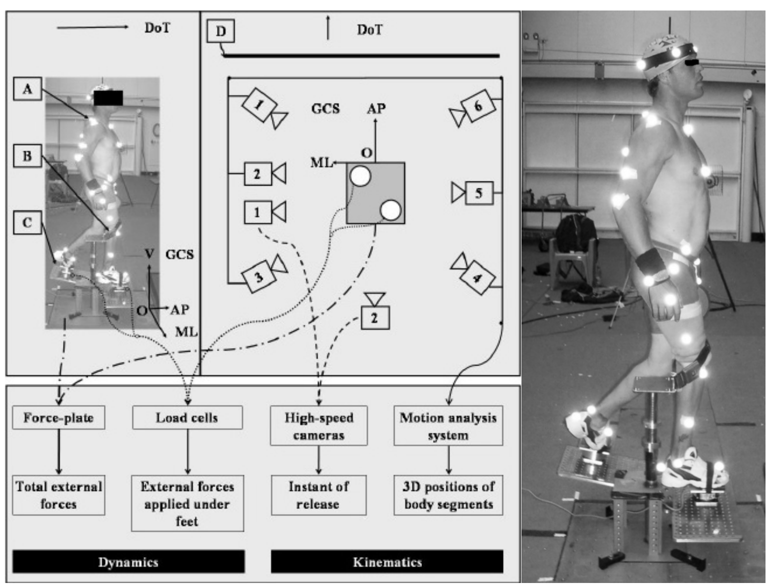


Figure 3 3: Adjustable throwing frame designed and used for research purposes ((Frossard, O'Riordan and Goodman 2005; Frossard, O'Riordan and Smeathers 2012a and 2012b) to investigate favourable feet positions for seated discus throwers. The throwing frame was also used for in-training and in-competition environments.

Table 3 7: Throwing frame design – Cluster 6 (n=9).

Study	Type of study	Topic/ Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Strengths	Limitations	Opportunities for further study
			n=3 male Elite	**During training** 7 testing sessions in total - 7sec recording duration (as above) Caibration frame used; Different foot positions trialled	2x digital cameras (50Hz); front on & side on; syncronised using Dartfish	Segmental angles of lower limbs in sagittal plane; Movement pathway of Hip & upper limbs	N/A	Informed parameters for **In Lab** & **In Comp** testing - (1) 5 key feet positions; (2) parameters to extract from video recording during real-events		MDT assembly including coaches, athletes, biomechanists, engineers	2D only - does not allow for motion in transverse plane; No reflective markers used; No kinetic data; limited subject no	Using more cameras
Frossard, O'Riordan, Goodman (2005)	Descriptive	describe the procedure, outcomes & limitations of the conventional approach, based on fundamental research	n=2 male Elite F34 athletes	**In Lab** 3x testing sessions focussing on foot placement; Anthrop measures taken; 10 throws in 5 diff feet positions (lots of rest);	1x Kister force plate (1080 Hz)-total external forces & moments; 2x load cells (100Hz)-forces under each foot; 2x Redlake highspeed camera (150Hz)-point of release; 12x Vicon cameras (120Hz)-3D coordinates.	N/A	N/A	Performance level of athletes improved as a result of testing & evidence based provision of information.	Loading profile at 3 pts of contact (2x feet+back of knee) - Magnitude of load at contact pts on release important; Range of movement, linear & ang velocity & momentum & CoM of each segment; Release parameters of	Evidence based approach (1) Improves modelling & performance prediction; (2) Informs athletes & coaches of technique relating to frame design; Throwing frame design - a fully adjustable frame was made for the research.	limited subject no	More In Lab testing in association with In Comp capture
			n=12 male Elite F33/34 discus throwers at 2002 WCs	**In Competition** Video footage of all athletes competing in F33/34 discus competition	2x digital cameras (50Hz); front on & side on as close to throwing plate as possible; syncronised using Dartfish.	2D coords of heel, top of foot, ankle of both feet tracked frame by frame; Qualititive analysis of performance against; (1) no of Lfoot, Rfoot, knee, buttock, arm-rest; (2) type of contact (strapped, locked, tucked) (3) Foot position (distance & angle).	N/A	Performance against resultant, vertical, a-p & m-l components of back & front feet positions.	No definite link between feet position & performance; Feet position is related to functional level & physical ability	3 x Testing environments including during training, in lab & during competition	2D only; No reflective markers used;	More in Comp capture & analysis

Frossard, O'Riordan, Goodman (2009a) Frossard, O'Riordan, Goodman (2009b) Frossard, O'Riordan, Goodman (2009c)	Descriptive	Provide coaches, athletes, sports scientists & classifiers true determinants of perf including (1) Release parameters (2) sequencing of actions prior to release (3) throwing frame design.	n=103 (77M & 26F) with 600 attempts across 10 classes (F33, 34, F52-58) from 14 events (10xSP, 3xDT, 1xJT)	From 2006 IPC WCs. Performances taken from official result sheets	2x digital cameras (50Hz); front on & side on; syncronised using Dartfish	Independent - Classification; gender Dependent - performance (m)	**Inter-Class Analysis** *Perf distribution in relation to:Class-to-Class & Gender-to-Gender; Class-to-Group of disability distribution; **Intra-Class Analysis** *Perf data - Ranking, Attempt, Order, Other; Descriptive perf stats - no of athletes & throws, mean, SD, COV, Min, Max, Range; Distribution of perf.	Improve understanding for Evidence based classification & research. Facilitate training methods. Inform of interaction between technique & frame design.		World first of evidence based data gathering & information dissemination in the form of open access ebooks	Rules relating to seated throwing & classification have been updated since this data collection	Evidence based data gathering from each major champs with current rules.
Frossard, O'Riordan, Goodman (2010)	Descriptive	n=55 male shot putter (F33&34) & (F55-58)	*to present a cataloguing of characteristics of throwing frames used by seated shot-putters. *to provide raw characterisati ons of the throwing frames for a group of athletes who participated in a world- class event.	6 stage heuristic approach including (1) ID of all characteristics (2) Selection of key characteristics (3) Initial cataloguing (4) On-field observation during wc event (5) review of initial & final calaloging (6) Final individual characterisation.	1 x digital camera, sagital to thrower dependent on throw hand preference	3 main categories (i.e., whole body, foot and upper limb specific characteristics) and seven sub-categories.	Descriptive analyses (1) reporting the characterisation of the best athletes (Gold medallists) in each of the six classes (2) Frequency of characteristics - % attempts in relation to total no of attemps (only ↑ 80% reported)	Potential relationships between throwing frame characteristics, performance and classification were also identified, by looking at the profile of best athletes (gold medallists), the frequency of characteristics and several data sets.	Analysis of data sets relating to characteristics, performance and classification were inconclusive.	*Highlightes the difficulties of establishing links between throwing frame characteristics, performance & classification. *Some methodological elements of cataloguing and assessment of interaction between athlete and throwing frame might be transferable to other sports equipment for athletes with a disability such as wheelchairs (i.e., racing, rugby, archery). Large number of subjects & trials (n=55; t=215)	Outdated rules	*Include both genders, all levels of experience (i.e., beginner, emerging, elite) and all throwing events (i.e., javelin, discus, shot-put). *Throwing configuration (side on vs front on throwing positions/pole vs no pole) could be better described by looking at the actual angle of the hips and/or shoulders with throwing sector.
Chung, Lin, Toro, Beyene, Garcia (2010)	Descriptive	Designing a generic throwing frame that accommodates all athletes across all classifications	Info gathered from athletes & leading coaches	Designed in Solidworks Premium 2009 using design criteria; Fabrication involved plastic, steel, aluminium.	Info to be gathered at later date - at training camp/competiti on	N/A	N/A	* Have features allow athletes to perform optimally * Be safe, & adjustable for all athletes * The uniform frame to reduce inspection & set-up time	N/A	One of very few adjustable throwing frame designs	*Design based on small number of applied experts & athletes; *Had not be assessed in training or competition	Lower cost of production; should be lighter

Grindle, Deluigi, Laferrier, Cooper (2012)	Descriptive	Describe the design & user evaluation of adjustable throwing frame (HATC)	n=19 (18M, 1F), mostly novices - 2xParalympians. 53% SCI	Athletes to place throwing frame in position of choice & throw from it. Adjustments could be made between throws	Questionnaire & structured interview	N/A	N/A	*Comply with international competition regulations * accommodate a wide range of functional abilities & throwing styles *easily adjustable quickly, without releasing tie-down straps	Reported that HTAC allows for greater range of movement; adjustable holding bar & backrest considered best features.	One of very few adjustable throwing frame designs	*No evidence based data collected, just personal opinion *Too heavy & lack of transportability	*3D peformance analysis using the HATC *Use with elite level throwers
Tweedy, Connick, Burkett, Sayers, Meyer, Vanlandewijck (2012)	RCT	To establish 2 standardized throwing frame configurations (self-selected) for overhand seated throwing, with/without holding pole. Does hand speed at release facilitate perf for pole vs no pole conditions?	n=47 (non-disabled) males (21.9+ 2.6 yrs)	3 testing sessions (48hr recovery between); **1st session** - pole & no-pole for subjs to self select preferred seated condition- Seat angle/ backrest height/ pole posn **2nd session** - with pole in preferred seated condition; **3rd session** - no pole in preferred seated condition.	AUS (n=29) subjs - 3D 6 camera QSM (150 Hz); 32 relective markers EURO (n=18) subjs - 1x Basler video camers (100Hz)	Independent: Pole vs no-pole; Dependent: Hand release speed Control: throwing frame	A paired sample t-test was used to evaluate differences in hand speed between pole & no pole conditions.	Primary outcome: HAND speed at RELEASE for pole vs no pole conditions.	Results from this study do not indicate whether it is more advantageous to throw with or without a pole.	*Established the seated throwing configurations preferred by non- disabled people, providing a valid guide for researchers wishing to evaluate the impact of impairment on seated throwing performance independent of throwing frame configuration. *Results do not indicate whether it is more advantageous to throw with or without a pole. *Large subject no; standardised throwing frame.	*non-disabled subjects; *inexperienced at seated throwing (although familiarisation given); *overhead ball throwing not a seated throws event;	Comparison to disabled subjects particulary seated throwers
Freitas, Abreu, Souza, Donega & Araujo (2015)	RCT	Compare the pressure distribution between a throwing frame seat & an adjustable anthropometric device in F56 seated throwers.	n=3; Male F56; age (23.33 ± 8,73 years)' weight (56.33± 5.50 kg)		Force Sensing Resistor (FSR) device placed on seat; 27 sensors along 340x340cm surface; Analysed using Labview	Throwing frame & adjustable seat, 2 sitting platforms	(1) Descriptive - mean & sd; (2) Paired t test - to verify correlation between variables of load distribution in 2 seat positions	Sitting pressure from 2 different seats	(1) Adjustable seat - distributed balanced pressure across 2 ischial regions & thigh; (2) Throwing frame focused on small area of one ischium	(1) Reduce pressure by distributing it over a larger area; (2) Help understand interaction between throwing technique & design of throwing frame (3) prevent pressure sores; (4) improve comfort. Provided some information on pressure distribution during sitting for spinal injured athletes	No info provided on if subjects (1) performed a throw; (2) the event; (3) no of trials; (4) performance	Greater number of subjects; Pressure distribution across all throwing phases

Chung, Lin, Toro, Beyene and Garcia (2010) designed an adjustable throwing frame, known as the highly adjustable throwing chair (HATC), based on recommendations from disabled athletes and expert coaches/practitioners. The intention was to design an adjustable throwing frame that could cater for all athletes of differing functional abilities, built according to international sporting standards, was safe, and allowed athletes to perform favourably. There was no information provided on the throwing frame characteristics that may assist with performance, or indeed, how this would be quantified or measured.

A user evaluation of the HATC was later conducted involving 19 seated throwers (18 male, one female) taking part in a national level training camp and competition (Grindle, Deluigi, Laferrier and Cooper 2012). Most of the throwers (n = 17) were novices with only two being at the Paralympic level. Key features of the HATC included an adjustable holding pole and trunk support with both depth and height variations. The throwers were given the opportunity of self-selecting a preferred throwing position, and time to have some practice throws before the competition. Upon conclusion of the competition, the athletes completed a questionnaire and structured interview on their experience and opinion on the HATC. It was reported that using the HTAC allows for greater range of movement, with the adjustable holding bar and backrest considered the best features. All information was based on personal opinion, which for athletes with impairments and limited sensation maybe difficult to quantify.

Future studies utilising 3D analysis of athlete performance throwing from the HATC would develop a better understanding of whether an adjustable throwing frame would be a viable option for seated throwers. From a functional perspective, a throwing frame that was light, compact and easily transportable would be beneficial (Grindle, Deluigi, Laferrier and Cooper 2012).

A comparison of seated pressure distribution between a throwing frame and an adjustable anthropometric device was conducted using a small number (n = 3) of elite athletes in one particular class (F56), a class associated with athletes that have full trunk but no leg or hip function (Freitas, Abreu, Souz, Donega and Araujo 2015). The purpose was to provide anthropometric information that might influence throwing frame design. Limited information was provided on how the data was collected, such as the design characteristics of either the throwing frame or the adjustable anthropometric device. Using several sensors to measure pressure distribution, results showed that pressure was more widely distributed across both ischial regions and thigh for the adjustable anthropometric device. This was different to the throwing frame where the pressure was directed in one small area of one ischium. No information was provided as to the ischium (left or right) being referred to and its relationship to the throwing arm. Despite the lack of clarity, this focus on seated pressure might assist in understanding the interaction between throwing technique and throwing frame design, in particular the seating orientation of the athlete, strapping location and strength. Research using sitting pressure mats would assist in developing this understanding for strapping placement.

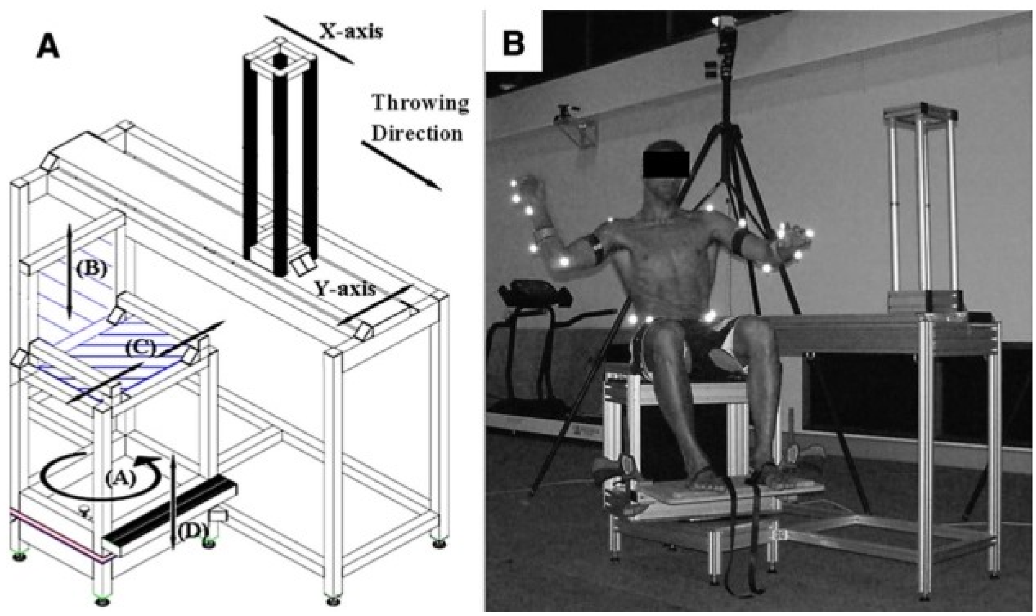


Figure 3 4: Adjustable throwing frame designed and only used for research purposes (Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck 2012; Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy 2016) to investigate favourable seating and holding pole position.

Other research has seen the use of an adjustable throwing frame that allowed for variations in seating orientation and holding pole position (Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck 2012; Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy 2016). In this instance, the throwing frame could only be used for research and was not suitable for use for training or competition (Figure 3 4).

The only commercially available adjustable throwing frame has been highly engineered and endorsed by England Athletics. It was designed based on the throwing characteristics identified by Frossard, O'Riordan and Goodman (2009a, b, c) and Frossard, O'Riordan and Goodman (2010) and my extensive involvement in coaching seated throwers. It was for athletics clubs to purchase, enabling participation of young seated throwers. It was not intended for elite level athletes but would allow for a template of throwing frame characteristics to be recognised for young and new throwers to then have their own bespoke model designed and constructed (Figure 2 2).

Cluster 7: Other research on other seated throws aspects such as throwing movement, coaching and classification

There are a number of studies focusing on other aspects of seated throwing (n = 11), with full details presented in Table 3 8. Competition footage (2002 IPC World Championship) and analysis appears within two later articles describing whether feet and whole-body position are important for performance (Frossard, O'Riordan and Smeathers 2012a and 2012b). The studies detail important characteristics relevant to overall throwing posture and lower limb placements and was the first to provide key information for improving the understanding of the interaction between throwing technique of elite seated throwers and their throwing frame.

Later articles involved data collection from major global competitions between years 2000 to 2008, such as Paralympic Games and World Championships. Mostly descriptive, the project started by sharing practical information on the systematic video recording of seated shot-putters during the Sydney 2000 Paralympic Games (Frossard, Stolp and Andrews 2004; Frossard 2006; Frossard, Smeathers, Evans, O'Riordan and Goodman 2008; Curran and Frossard 2012). The research involved the video recording, from the field of play, of 93 athletes. Whilst 72% of all trials were successfully recorded, the research team were able to make recommendations on how to improve the recording rate through several interventions. It resulted in the development of a six-step heuristic approach based on expert opinion and analysis of 215 trials from 55 male athletes across all seated shot-put classes (Frossard, O'Riordan and Goodman 2010). The process is still valid today despite the rule changes. and has provided the basis for much of the research that has taken place in more recent times, a number of which have focused on the impact of body position and throwing frame design might have on functional classification (Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck 2012; Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy 2016).

Table 3 8: Other research on seated throws aspects such as throwing movement, coaching, classification and seating pressure – Cluster 7 (n=11).

Study	Type of study	Topic/Research Question	Participants	Testing procedure	Method of data capture	Design (variables)	Stats	Outcome measures	Results	Conclusions	Strengths	Limitations	Opportunities for further study
Frossard, Stolp, Andrews (2004)	Descriptive	To share useful & practical information coming out of the first experience of systematic video recording of seated shot-putters during the Sydney 2000 PGs.	n=93 (F52-58 classes); 30xFemale - 63xMale	Video footage gained from the field of play, from 93 seated shotputters competing at the 2000 Paralympic Games.	2x high speed digital cameras (100Hz); front on & side on; 7s recording length (from time athlete was handed implement to it touching the ground)	Relating to trials - (1) Expected (2) Not recorded (3) Recorded - Incomplete/ Obstructed/ Useable	Descriptive - % relating to trials analysed	Success rate of video recording to analyses	15% of the attempts were not recorded, 72% were recorded & fully available for analysis, 10% were incomplete & 2% were obstructed (as a percentage of expected attempts)	(1) Assess thoroughly the feasibility of the cameras' positions prior to opt for a 3D video recording setup, (2) Use at least 2 cameras & preferably 4 cameras for a bi-planar analysis, (3) Place the cameras reaching the relevant field of view as close as possible to the plate, (4) Employ 2 operators per camera. One in charge of the recording while the other prevents interferences from the environment Provide formal information on the study to officials and broadcast TV crews prior to the event,	Data captured during WC event; Large subject number	2D only; No reflective markers used; Low capture rate	See conclusions
Frossard (2006)	Descriptive	n=93 (F52-58 classes); 30xFemale - 63xMale	Share useful & practical information coming out of the first experience of systematic video recording of seated shot-putters during the Sydney 2000 PGs.	Video footage gained from the field of play, from 93 seated shotputters competing at the 2000 Paralympic Games.	2x high speed digital cameras (100Hz); front on & side on; 7s recording length (from time athlete was handed implement to it touching the ground)	**Relating to trials** (1) Expected (2) Not recorded (3) Recorded - Incomplete/Obstructed/Useable	Descriptive - % relating to trials analysed	*Identify practical aspects of camera set -up to improve procedure used during systematic video recording during WC events *Identify number & usability of trials recorded	*15% of the attempts were not recorded, *72% were recorded & fully available for analysis, *10% were incomplete *2% were obstructed (as a percentage of expected attempts)	The increase of number & use of attempts recorded relies on number & position of cameras & operators Refer to Frossard (2004)	Data captured during WC event; Large subject number	2D only; No reflective markers used; Low capture rate	

O'Riordan & Frossard (2006)	Descriptive	n=1 Male F34 discus thrower	Compartive technical study - differences in technique 12 months apart	Video footage taken from same competition 12 months apart; Training programmes reviewed between the timeframe	2x digital cameras (25Hz); one at back, one on throwing side; syncronised using Dartfish		Descriptive	No of Preparation Phases; Foot position; Shot placement	Performance improvement	Provide general guidelines for: (1) throwing frame design & construction; (2) coach education for seated throwing (3) defining functional status of athlete, i.e. classificaiton	No other information available describing training of seated throwers	Only 1 athlete	There is a need for further longitudinal studies replicating the description of the whole body positioning, particularly those focusing on more recent female and male events, wider level of performance (e.g. beginner, emerging, elite), classification & events.
Frossard, O'Riordan, Goodman (2009a) Frossard, O'Riordan, Goodman (2009b) Frossard, O'Riordan, Goodman (2009c)	Descriptive	Provide coaches, athletes, sports scientists & classifiers true determinants of perf including (1) Release parameters (2) sequencing of actions prior to release (3) throwing frame design.	n=103 (77M & 26F) with 600 attempts across 10 classes (F33, 34, F52-58) from 14 events (10xSP, 3xDT, 1xJT)	From 2006 IPC WCs. Performance s taken from official result sheets	2x digital cameras (50Hz); front on & side on; syncronised using Dartfish	Independent - Classification; gender Dependent - performance (m)	**Inter-Class Analysis** *Perf distribution in relation to:Class-to-Class & Gender-to-Gender; Class-to-Group of disability distribution; **Intra-Class Analysis** *Perf data - Ranking, Attempt, Order, Other; Descriptive perf stats - no of athletes & throws, mean, SD, COV, Min, Max, Range; Distribution of perf.	Improve understanding for Evidence based classification & research. Facilitate training methods. Inform of interaction between technique & frame design.		World first of evidence based data gathering & information dissemination in the form of open access ebooks		Rules relating to seated throwing & classification have been updated since this data collection	Evidence based data gathering from each major champs with current rules.

Frossard (2012)	Retrospective	n-114 (M&F); from F32-34 & F52-58; t=479	(1) describe tools designed to comprehend & represent the dispersion of the performance between successive classes (2) present this dispersion for the elite male & female stationary shot-putters who participated in Beijing 2008 PGs.	n=114 from 8 seated shot events (F32-34, F52-58); All successful trials included.	Performances taken from official result sheets	Independent - Classification; gender Dependent - performance (m)	The inter-dispersion of the performance of M & F was analysed through complementary tools: comparative matrices, performance continuum & dispersion plots.	Provides some tools capable of providing an overview of the inter-dispersion of classification-related variables - comparative matrices, performance continuum & dispersion plots.	Demonstrated a linear relationship between best performance & classification. Revealed 2 male gold medallists in F33 & F52 classes as outliers.	This was the first attempt to describe the inter- dispersion of the performance of male and female athletes participating in the stationary shot-put events during the Beijing 2008 Paralympic Games.	Large number of subjects & trials (n=114; t=479). Elite athletes used.	Conducted with outdated rules	And/or shoulders with the throwing sector. Design of the throwing frame, e.g. feet position, the seating arrangement & use of holding pole
Frossard, O'Riordan, Smeathers (2012a)	Descriptive	n-=12 Male seated discus throwers (F33 & 34)	Benchmark information about performance & whole body positioning of male athletes in F30s classes.	48/59 trials (successful trials only used) from 12 seated discus throwers (F33& F34); 2002 WCs	2x digital cameras (25Hz); one at back, one on throwing side; syncronised using Dartfish		Intra-attempt i.e. the attempt-to-attempt variability of the performance for each athlete was described by the number of attempts analysed, the mean, one standard deviation, the minimum (worst attempt), the maximum (best attempt) & performance range.	(1) **Overall Throwing Posture** (i.e. number of contact pts between thrower & frame, body position, throwing orientation & throwing side) (2) **Lower Limb Placements** (i.e. seating arrangements, points of contact on the both feet, type of attachment of both legs and feet).	**Overall Throwing Posture** (1) **Pts of contact:** All athletes relied on at least 3 points of contacts, including the 2 feet. 3(25%); 5(42%); 1(8%); 3(25%) athletes used 3-6 contact pts; (2) **Standing** vs **sitting** posn - 7 athletes (58%) vs 5 athletes (42%); (3) Front-on vs Side-on - 8 athletes (67%) vs 4 athletes (33%) (4) L vs R handed - 5 athletes (42%) vs 7 athlete (58%). **Lower Limb Placements** (1) Type of frame: Straddle - 6 athletes (50%); Stool - 4 athletes (33%); Chair - 2 athletes (17%); (2) Front foot PT of contact: 5th metatarsal - 10 athletes (83%); Heel - 2 athletes (17%); (3) Front foot TYPE of contact: Free - 1 athletes (8%); Locked -1 athletes (8%); Strapped - 4 athletes 42%); Tucked -4 athletes 42%) (4) Back foot PT of contact: 5th metatarsal - 9 athletes (92%); Heel - 1 athlete (8%); (5) Back foot TYPE of contact: Free - 6 athletes (50%); Locked -2 athletes (17%); Strapped - 4 athletes (33%);	The whole body positioning of stationary discus throwers in F30s classes during actual world-class event has been described for the first time. It is anticipated that the results of this study will provide key information to those facing the challenge of improving the understanding of the **interaction between throwing technique of elite seated throwers & their throwing frame.**	Provides benchmark info to athletes, coaches, classifiers, biomechanists, officials & other participants for (1) evidence-based training programs, (2) design of the throwing frames, (3) rule of discus throwing event for athletes in F30s classes.	Small number of participants limited further statistical cluster analyses. Data collected in 2002 - rules have changed since this time.	*There is a need for further longitudinal studies replicating the description of feet positioning, particularly those focusing on more recent female and male events, wider level of performance (e.g. beginner, emerging, elite), classification & events). *Further cross-sectional studies to be conducted in experimental conditions with further 3D kinematic (e.g. position & orientation of each segment) & dynamics (i.e. contact external forces & moments).

Frossard, O'Riordan, Smeathers (2012b)	Descriptive	n-=12 Male seated discus throwers (F33 & 34)	(a) to benchmark feet positioning characteristics (i.e. position, spacing & orientation) (b) to investigate the relationship between performance and these characteristics.	48/59 trials (successful trials only used) from 12 seated discus throwers (F33& F34); 2002 WCs	2x digital cameras (25Hz); one at back, one on throwing side; syncronised using Dartfish	0	Intra-attempt i.e. the attempt-to-attempt variability of the performance for each athlete was described by the number of attempts analysed, the mean, one standard deviation, the minimum (worst attempt), the maximum (best attempt) & performance range.	Further analyses will provide a better understanding of the relationship between performance and design of the throwing frame.		*Provides quantitative descriptions of actual 3D feet positions, spacing & orientation used in competition. These results confirmed that the so-called base of support of discus throwers could not only be described by feet positioning but also by whole body positioning. *Demonstrated links between feet positioning & performance were weak, despite that the performance progressing regularly upwards within the range of 16.35 m between the worst & best performances. This weak relationship might be due to the shortcoming of the analysis as detailed further in section about the limitations.	Provides key information to those facing the challenge of improving the understanding of the interaction between seated throwing technique & throwing frame	Small number of participants limited further statistical cluster analyses. Data collected in 2002 - rules have changed since this time.
Curran & Frossard (2012)	Expert opinion	Emerging & Elite Para athletes	Describes video capture procedure from 2000 PGs	Dialogue with experienced biomechanics researcher & practictioner working in the field of Para Athletics	Interview	N/A	N/A	*Contribution of biomex to understanding performance of Para athletes, & use as an evidenced based tool. *Reliability for performance for 2D vs 3D analysis. *Guidance on approaches for biomex/PA analysis for Para Athletes.	See outcome measures	(1) the practical aspects of the cameras' setup used during this systematic video recording. (2) the number & usability of attempts recorded, taking into consideration the impact. (3) recommendations to improve the video recording procedure in such conditions.	Unique approach to dessimiating this kind of information. It supports more research based information delivery	Could be considered as subjective as only one opinion

Freitas, Abreu, Souza, Donega & Araujo (2015)	RCT	Compare the pressure distribution between a throwing frame seat & an adjustable anthropometric device in F56 seated throwers.	n=3; Male F56; age (23.33 ± 8,73 years)' weight (56.33± 5.50 kg)	Force Sensing Resistor (FSR) device placed on seat; 27 sensors along 340x340cm surface; Analysed using Labview.	Throwing frame & adjustable seat, 2 sitting platforms	(1) Descriptive - mean & sd; (2) Paired t test - to verify correlation between variables of load distribution in 2 seat positions	Sitting pressure from 2 different seats	(1) Adjustable seat - distributed balanced pressure across 2 ischial regions & thigh; (2) Throwing frame focused on small area of one ischium	(1) Reduce pressure by distributing it over a larger area; (2) Help understand interaction between throwing technique & design of throwing frame (3) prevent pressure sores; (4) improve comfort. Provided some information on pressure distribution during sitting for spinal injured athletes	Provided some information on pressure distribution during sitting for spinal injured athletes	No info provided on if subjects (1) performed a throw; (2) the event; (3) no of trials; (4) performance	Greater number of subjects; Pressure distribution across all throwing phases

There appears to be only one article relevant to the coaching of seated throwers (O'Riordan and Frossard 2006). The article is an expert piece describing the improvement in performance that occurred over a 12-month period because of technical, throwing frame design and training interventions. Interestingly, it has the most reads of all the current research into seated throws, according to research-based websites such as Orcid and Researchgate. This might suggest, that more applied research that can be used by coaches and athletes to improve performance, would be of interest and benefit. This article has recently been updated and it includes some of the findings of this thesis (O'Riordan and Frossard 2020a). Thus it is not included in the literature review as an intention of the review was to inform the thesis study design.

3.4 Conclusion

As previously mentioned, the rules governing both seated throwing technique and throwing frame design (Table 2 2) have changed a number of times since 2000. This means that the seated throwing events have become more constraints-led due to the movement limitations placed on the athlete in terms of seating position and points of body contact. This, in turn, has resulted in technical changes affecting performance. In most cases, performances have decreased over time for those classifications that were able to utilise their legs more, due to these heightened constraints, as shown by the results from major championships.

There is a need for better understanding of the interaction between the three levels of constraint i.e. the organism (the athlete), the environment and task. Additionally, more research is required to explain further inter-segment co-ordination patterns and how they combine to influence the kinetic chain and improve performance (Keogh and Burkett 2016; Morrien, Taylor and Hettinga 2016). As the use of a throwing frame for seated athletes is a requirement of the rules of the sport, it would appear essential then that the interaction of the throwing frame and the athlete in terms of technique, becomes even more important for performance improvement, and worthy of further research.

In summary, of the 26 pieces of research reviewed, relating to seated throwing:

- there was limited research involving 3D data collection (n=4).
- all research is pre the 2014 rule change which affected both technique and throwing frame design, so is only partially relevant at this time.

- there is more research on the release variables when compared to kinematic variables.
- there is limited research on the linear kinematics of upper body segments and their contribution to the seated shot-put throwing pattern. Thus, any angular kinematic analyses previously conducted may have been completed without a full understanding of the linear kinematic motion that underpins it.
- there are limited technical recommendations generated for athletes and coaches.

Based on the findings from the literature review, key focus positions (Tiers 1, 2 and 3) were identified as shown in Figure 3 5, and described below.

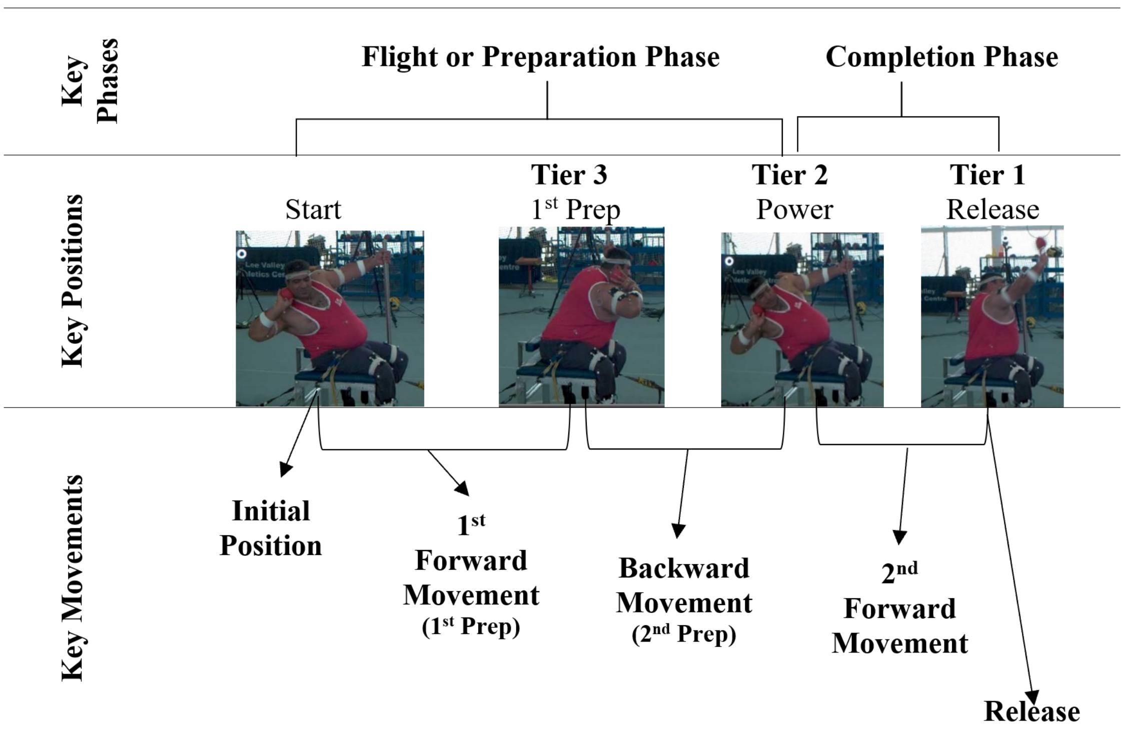


Figure 3 5: Visual representation of Tiers 1, 2 and 3, and how they related to the whole throwing movement for seated shot-put.

A deterministic model of seated shot-put was created based on these three tiers (Figure 3 6), and the model informed the study design. The model addresses the gaps in the literature, and based on the earlier model of Chow, Chae and Crawford (2000), its purpose is to identify and inform important aspects of technique to positively influence performance. It will provide the basis for technical considerations for athletes and coaches, especially around seating configuration, and includes:

- Tier 1 is the point of shot-put release and is at the end of the delivery phase. The shot-put release variables considered include velocity (horizontal, vertical and resultant), angle, height which contribute to the flight distance, together with the gain (the actual release point ahead or behind the line of measurement) which determines the overall throwing performance. It is a more traditional discrete analysis of the data and makes up Study 2 in this thesis.

- Tier 2 is the power position, which occurs at the end of the 2nd preparation phase. It starts the completion phase which is the movement from the power position into the release. The linear kinematics of key joints (trunk, shoulder, elbow and shot-put/hand) are considered to see how they might influence the completion phase, i.e. from the power to the release position, and how these might impact on the release parameters are of interest, and feature in Study 3.

- Tier 3 is the 1st preparation position, which occurs at the end of the 1st preparation phase. The linear kinematics of key joints (trunk, shoulder, elbow and shot-put/hand) are considered to see how they might influence the 2nd preparation phase i.e. from the start to the 1st preparation position, and then ultimately the delivery phase. It will make up Study 3.

Traditionally, the focus of most biomechanical research on shot-put has been on discrete variables, particularly the parameters of release i.e. height, angle and velocity. This thesis will include an analysis of release variables specific to seated shot-put, and is based on Tier 1, the release, of the deterministic model (Figure 3 5), and is addressed in Study 2.

There is minimal research addressing the movement characteristics of seated shot-putters and its impact on both throwing technique, particularly since the rules changed in 2014. This thesis will provide the most up-to-date information, based on current rules. In Study 3, the focus will be on movement differences throughout the whole throwing movement from a linear kinematic point of view including displacement, velocity and temporal variables of key upper body segments and the shot-put.

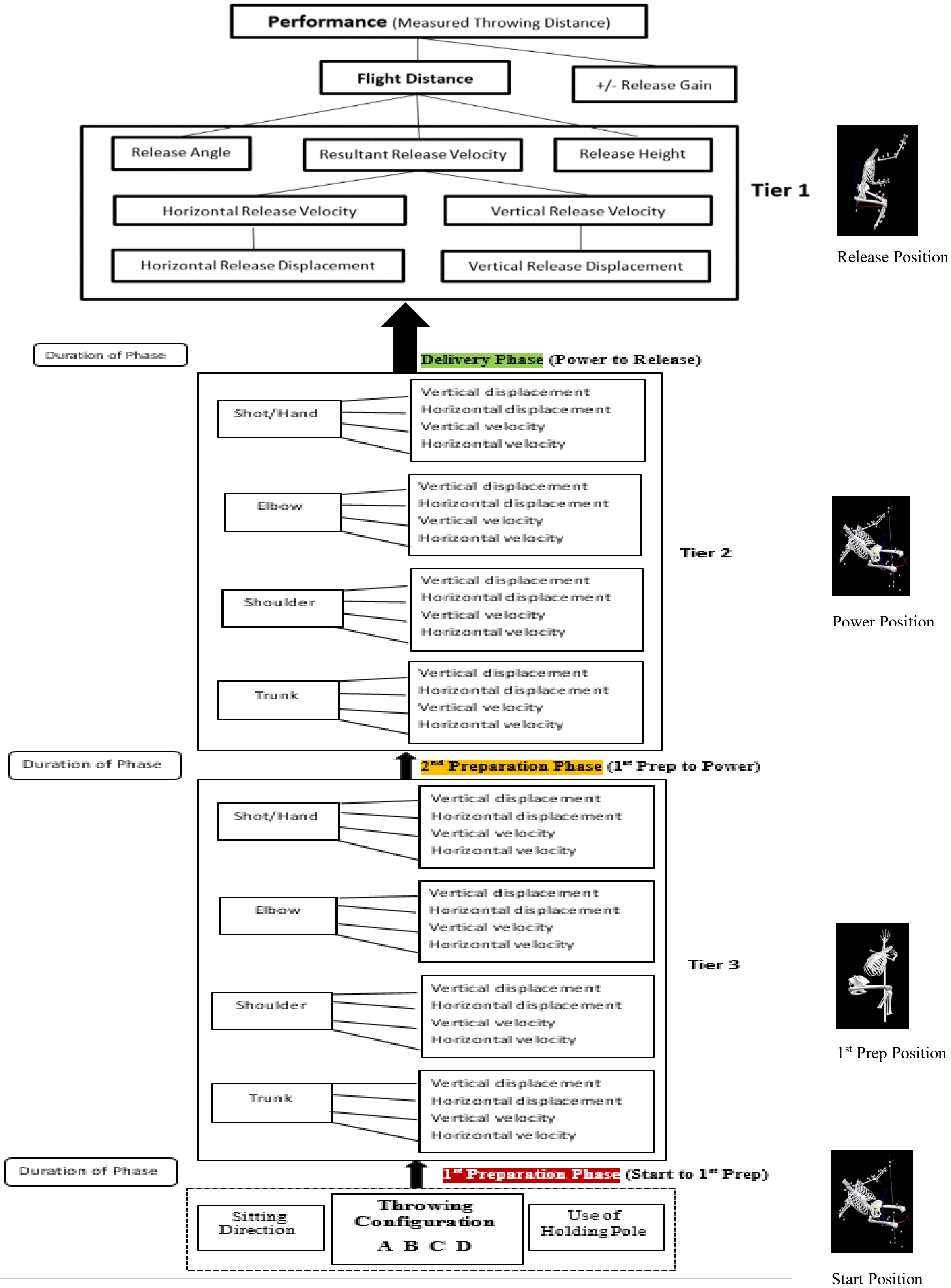


Figure 3 6: Deterministic model for seated shot-put created from seated throws review of literature.

Chapter 4: Study 1

Methods: From pilots to protocol

Some outcomes of this chapter are presented in the following publication:

- O'Riordan A and Frossard L (2020c) - Inter and intra variability of release variables of the shot-put's trajectory of elite seated shot-putters throwing from different seating configurations, *Mendeley Data, VI*, doi:10.17632/65ctb4dzcn.1.

The content of this chapter will be presented in the following publications:

- O'Riordan A and Frossard L – Performance of elite seated shot-putters: Hold onto the pole: A case study. To be submitted to *Journal of Sports Science* in February 2021.
- O'Riordan A and Frossard L – Impact of Seating Configuration on performance: an elite seated shot-putter's case study. To be submitted to *Journal of Sports Science* in March 2021.
- O'Riordan A and Frossard L - Computing performance of elite seated shot-putters: can the blue box be trusted. To be submitted to *Sports Biomechanics* in April 2021.

Abstract

Aim: To inform methodological constructs for cutting-edge biomechanical analyses of seated shot-putters through three preliminary studies. ***Methods***: Study 1A involved one elite male Class F55 participant performing six trials from two seating positions. 3D kinematic data were collected using a 10 camera (250 Hz) Qualisys Motion Capture System equally spaced around the throwing frame. Study 1B involved one elite female Class F34 participant performing six trials from four seating configurations (A, B, C and D). The same 3D capture system was used as above included more cameras. Study 1C involved eight elite level Class F55 and F56 participants. Using the same capture system as in Study 1B, each participant performed six trials from the same seating configurations. Using equations of parabolic flightpaths calculated performance was compared to the measured performance. ***Results***: Study 1A recommended larger reflective markers to be employed for the ASIS joints and for cameras to be increased from 10 to 20. Study 1B consolidated the above recommendations and showed noticeable differences in movement characteristics between the seating configurations, making them suitable for inclusion into the future studies. Study 1C demonstrated that considering a longer flight trajectory (10 frames post release) reduced the error between calculated and manually measured performances, thus increasing the accuracy of the shot-put release variables. ***Conclusion***: Recommendations from Study 1 were critical to inform the design of subsequent observational cohort Studies 2 and 3. Study 1A and 1B were helpful in determining the placement and size of reflective markers placed on body landmarks particularly around the pelvis, as well as the number of cameras needed to capture the whole throwing motion. Exploratory data were generated on the sitting direction and holding pole use which provided valuable insights into seating characteristics. Study 1C provided a practical way to minimise error when comparing calculated to manually measured performance.

4.1 Study 1A – Exploring methodological protocols around the set-up design for 3D kinematic measurement of seated shot-putters.

4.1.1 Introduction

There is a very small amount of research involving 3D capture and analysis of seated throwers (n = 4), as identified in Chapter 3. All of this research was undertaken prior to the most recent rule change in 2014 (Table 2 2). Studies conducted prior to the rule changes have limited relevance, particularly so as one of the major differences in the rules is that athletes now have to remain seated at all times throughout the throwing movement. This is of even more importance as much of the earlier research was conducted on athletes that had some leg function (Chow, Chae and Crawford 2000; Frossard, O'Riordan and Goodman 2005; O'Riordan and Frossard 2006, Frossard, O'Riordan and Smeathers 2012a and 2012b). The athletes were often able to release in a standing position and permitted to do so by the rules at that time.

There is a need for more biomechanical research on inter-segment co-ordination patterning, the use of the kinetic chain (Keogh and Burkett 2012) and by linking controlled in-lab outcomes to in-training and in-competition environments (Morrien, Taylor and Hettinga 2016). As athletes now have to remain seated, more relevant 3D biomechanical analysis is a priority. The 3D tracking of the pelvis region is of interest as it could be more problematic for participants with lower thoracic spinal injury throwing from a seated position, as for those in Class F55.

The use of a holding pole is one seated frame characteristic that some athletes utilise, mostly for balance and/or to generate driving forces (Frossard, O'Riordan and Goodman 2005). Thus, those athletes with full trunk function maybe less likely to use one, but this is not always the case as seen by viewing competition footage from global games.

Subsequently, there is a need to explore further methodological considerations. Of particular interest is the key interaction between the seated thrower and their throwing frame, as recommended by Keogh and Burkett (2016). This will enable evidence-based decisions regarding throwing technique and frame design by the coach and athlete, to influence performance.

Skin mounted reflective markers are usually used, along with a 3D motion capture system to determine the kinematics of the shoulder and trunk in sporting movements (Karduna, McClure, Michener and Senet 2001; Senk and Cheze 2006 in Jackson, Michaud, Tétreault and Begon 2012; Joyce, Burnett, Cochrane, Ball and Ball 2013). To define shoulder and trunk segments and describe their related motion, Wu, Siegler, Allard, Kirtley et al. (2002) and Wu, van der Helm, Veeger, Makhsous, et al. (2005) generated recommendations for standardised joint co-ordinate systems based on anatomical landmarks. These recommendations were used within Study 1, 2 and 3.

In biomechanical studies of athletes from other seated sports, Bjerkefors , Rosén, Tarassova, and Arnd (2015) used 12 infrared cameras when conducting a comparative analysis of elite kayakers and para-kayakers using stationary ergometers whereas Jones, Allanson-Bailey and Holt (2010) used eight cameras in their study on female rowers. Based on these earlier studies on seated athletes from other sports, it was decided that 10 cameras would be used for the first feasibility study (Study 1A). It was anticipated that all reflective markers would be viewed easily throughout the whole throwing movement as the environment is stationary i.e. the participants will be seated and not ambulatory.

The theoretical principles underlying the 3D measurement of the kinematic variables of a seated shot-putter are discussed below with reference to the co-ordinate system. Kinematic information is particularly important as it allows for the throwing technique implemented by a given athlete to be described in detail through a three-dimensional analysis of movement utilising six degrees of freedom (McGinnis 2005; Payton and Bartlett 2008; Richards 2008).

When using 3D capture and analysis it is important to understand the co-ordinate systems that are utilised by the analyses software systems to generate the tri-dimensional data. Three collinear coordinate systems are necessary to describe the kinematics of seated shot-putters (Figure 4 1) including;

- Global Coordinate System (GSC - [O, XO, YO, ZO]), is the fixed inertial referential located at the central point on the seating area of the throwing frame.
- Local Coordinate System (LCS - [G, XG, YG, ZG]) is located at the centre of mass of the whole-body G.
- Segmental Coordinate System (SCSi - [Si, XSi, YSi, ZSi]) of each segment is located at the centre of mass Si of this segment.

The athlete's body can be considered as an articulated multi-body system Sa of mass Ma composed of 16 solid segments Si of mass mi linked by internal forces.

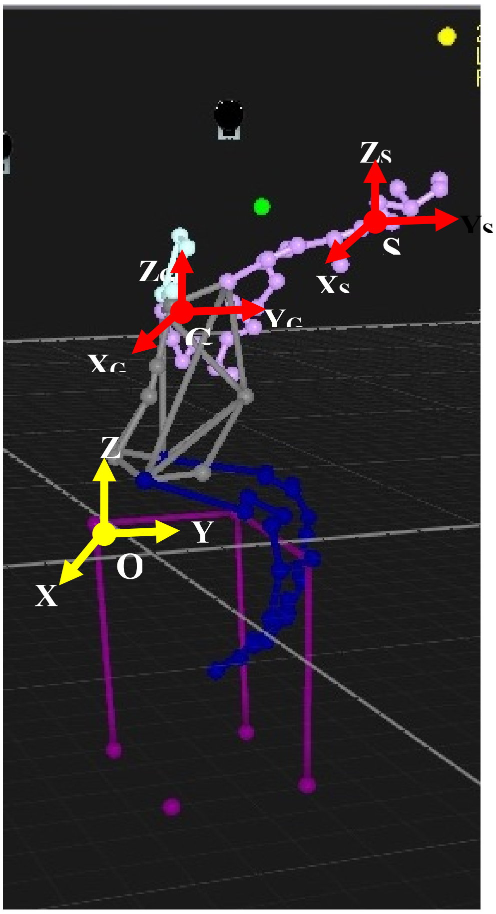


Figure 4 1: Systems of referential including the Global Coordinate System (GSC - [O,XO,YO,ZO]), Local Coordinate System (LCS - [G, XG, YG, ZG]) and Segmental Coordinate System (SCS - [S, XS, YS, ZS]).

Purposes

The main purpose was to explore ways to conduct 3D kinematic measurement of seated shot-putters, including the positioning of a holding pole.

Objectives

The specific objectives considered were:

- the numbers and locations of reflective markers around the shoulder and pelvis,
- the number and placement of cameras.

4.1.2 Methods

Participants

One male elite level Class F55 right-handed seated shot-putter participated in this study (Age 39 years, Height 2.17 m, and Mass 145 kg). Standard informed consent procedure was followed in accordance with the ethical approval given by the Middlesex University LSI Ethics Committee (Appendix A). At the time of testing, the participant was one of only two elite seated shot-putters in the UK, and the only one in this class.

The participant was required to attend a single testing session which included six maximal throws from two different throwing configurations (known as Condition 1 and 2), thus n = 12. The throwing frame had the capacity to allow for the holding pole to be fixed in two different positions 5 cm apart. In Condition 1, the further holding pole position, was fixed to the very front of the throwing frame on the non-throwing side (Figure 4 2). In Condition 2, the nearer holding pole position was fixed 5cm in from the front of the throwing frame. This meant it was closer to the non-throwing hip of the participant. There is currently no information available to inform the positioning of the holding pole for favourable performance.

Apparatus

The participant threw from his own throwing frame which complied with World Para Athletics rules governing throwing frame design (World Para Athletics 2020 - 21) and had been used in international competition. The throwing frame was 75 cm maximum height from the ground to the sitting surface, and had a rigid, solid holding pole. The frame was secured to the ground using ratchet straps from each corner of the frame into purpose built eye bolts set in concrete (Figure 4 2).

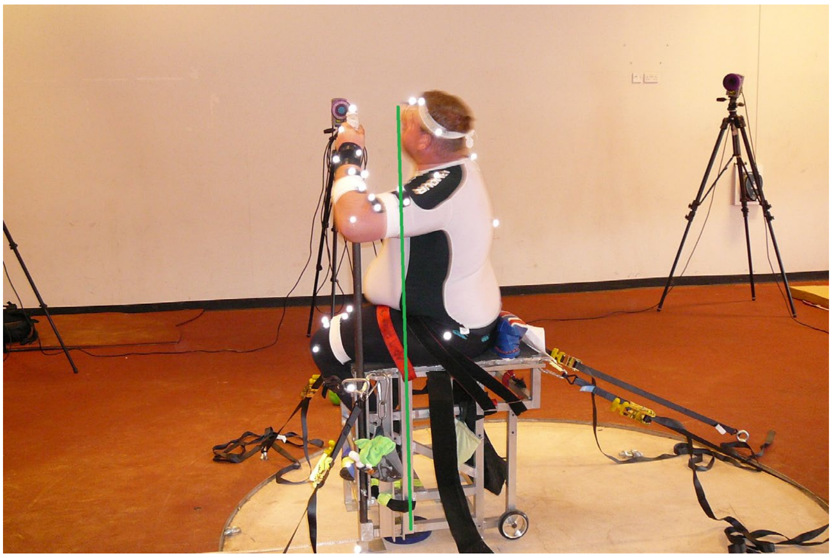


Figure 4 2: Testing set-up showing participant seated on their own throwing frame secured to the ground, with holding pole fixed to front end of the frame. Also shown, the different holding pole positions. Participant is holding pole at Condition 1 whilst green line highlights Condition 2.

Recording

For ease and accuracy of reflective marker placement and to simulate competition, the participant wore close fitting competition clothing, such as a singlet, leggings and their usual footwear. In accordance with International Society of Biomechanics (ISB) recommendations (Wu, Siegler, Allard, Kirtley et al. 2002; Wu, van der Helm, Veeger, Makhsous, et al. 2005), 81 whole body reflective markers, as detailed in Table 4 1, were placed on the participant and equipment. Details on how the reflective markers were positioned are in Appendix B4.

Table 4 1: Reflective marker set-up for participant and equipment.

Trunk - (5 reflective markers)
- Acronium process – Right and Left
- The Spinous Process of the 7th cervical vertebra - C7
- The Spinous Process of the 10th thoracic vertebra – T10
- Xiphoid process, distal end

Pelvis (R and L) - (6 reflective markers)
- Greater Trochanter
- ASIS
- PSIS

Lower limbs (R and L) - (28 reflective markers)
- Thigh cluster (4 reflective markers)
- Condyle of the femur – lateral and medial
- Shank cluster (3 reflective markers)
- Malleolus – lateral and medial
- Base of 1st and 5th phalange
- Calcaneus

Upper Limbs (R and L) - (26 reflective markers)
- Upper Arm cluster (4 reflective markers)
- Lateral and medial epicondyle of humerus
- Lower Arm cluster (3 reflective markers)
- Radius-Styloid process
- Ulnar-Styloid process
- Base of 1st and 5th metatarsal

H**ead -** (4 reflective markers)
- Anterior and Posterior – Right and Left

Equipment – (12 reflective markers)
- Corners of throwing frame – top and bottom
- Holding Pole (top, middle, bottom)
- Shot -put.

The participant was asked to hold a seated, static anatomical position for a period of five seconds, which was recorded by the Qualisys system in order to construct a static model, as described later (Figure 4 3). After conducting his usual warm-up, the participant was asked to throw six maximal throws from Conditions 1 and 2. In-competition conditions were followed in terms of times allowed to start throwing after securing the throwing frame, and between throws as per the event rules (World Para Athletics 2020 – 2021). Adequate rest between the testing conditions was allowed to avoid fatigue (Craig, Tran, Wiliesuriva and Middleton 2012).

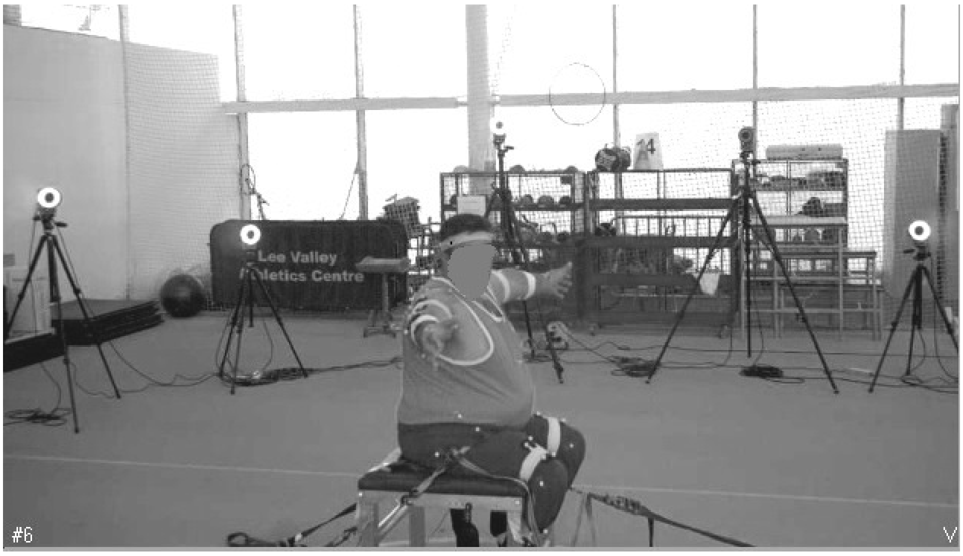


Figure 4 3: Participant holding static, seated anatomical position.

Distance thrown was recorded after each trial by manually marking and measuring with a tape from where the shot-put landed to the front of the circle, in accordance with the event rules (WPA 2020 – 2021). The participant threw from their usual sitting position, which was from a diagonal seating position in this case (Figure 4 4).

Three dimensional kinematics data were collected using a 10 camera (250 Hz) Qualisys Motion Capture System (Oqus 300/310, Qualisys AB, Gothenburg, Sweden) equally spaced around the throwing frame (Figure 4 4). The system was calibrated prior to capture in accordance with manufacturer's guidelines using their calibration wand method. This involved placing the L-shaped calibration device (mirrored L) on the seat of the throwing frame to create a global co-ordinate system. All markers on the calibration device were viewed by the cameras, which enabled the highest accuracy of the system. A calibration wand of 600.7 mm length was moved continuously around the entire measurement volume in all three directions for 10 seconds, which enabled the correct scaling of all axes. The measurement volume included the throwing frame with seated participant holding the release position (Figure 4 4). Calibration was accepted if average 3D residuals were estimated to be ≤1.0 mm.

Figure 4 4: Testing set up showing participant's diagonal seating position (front leg facing forwards and back leg facing diagonal to right side) and 10 cameras situated around the throwing area.

Processing

A static model was constructed in the Qualisys software, in order to define joints. The reflective markers were tracked by the system before being exported into standard motion analysis software (Visual3D, C-Motion, Inc. Maryland, USA). A ten-segment rigid body model of the upper limbs, trunk, pelvis, and lower limbs was created. A standard direct linear transfer method (Abdel-Aziz and Karara 1971) is used by the Qualisys software to generate the co-ordinates later used to construct a 3D model of the body via the Visual3D software. The kinematic video data were smoothed with a Butterworth digital filter, as described by

Winter, Sidwell and Hobson (1974). A favourable Butterworth low-pass filter (cut-off frequency of 8Hz) was selected to filter the kinematic data. The key events symbolising the power and release positions as described later and shown in Figure 4 5 were also identified with the Qualisys software.

Based on previous research of shot-put and other throwing activities involving non-disabled athletes (Bartonietz and Borgstöm 1995, Young and Li 2005; Judge, Young and Wanless 2011) the kinematic variables explored for Study 1A included trunk angle measured in degrees, and angular velocity of the trunk, shoulder and elbow, measured in degrees/s. The angular variables were determined using Visual 3D pipelines in the following way:

- Trunk – angle between the thorax/ab (segment) and pelvis (reference segment)
- Shoulder – angle between upper arm (segment) and thorax/ab (reference segment)
- Elbow – angle between upper arm (segment) and forearm (reference segment).

The throwing movement was broken down into two positions, Tier 2 (Power) and Tier 1 (Release) positions (Figure 4 5), which made up the completion phase, as described previously.

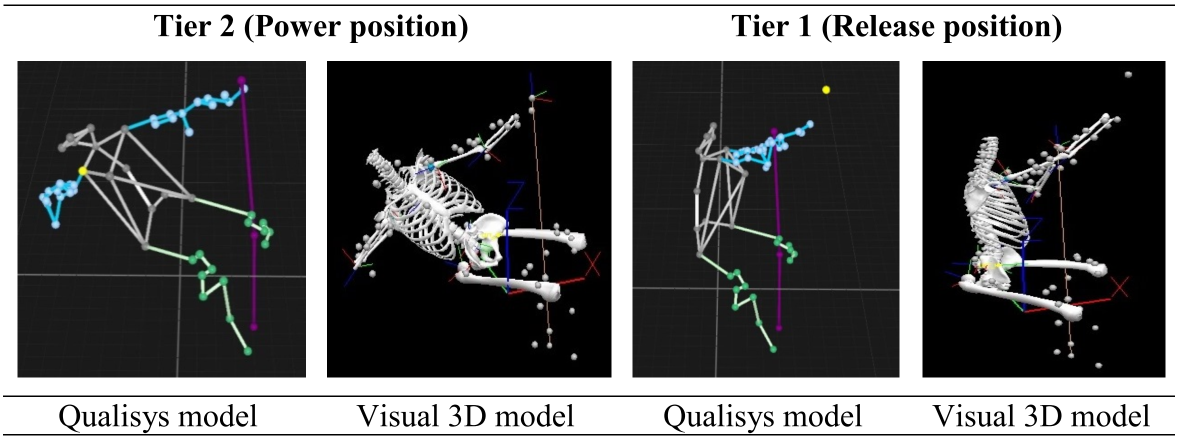


Figure 4 5: Power and Release position visuals using Qualisys and Visual 3D software.

The trunk angle and joint angular velocities for each trial was time normalised by interpolating to 101 data points using excel. The mean of the six trials was used for analysis, which was then presented and analysed graphically. Values at the peaks and troughs were generated from viewing both graphs and data. For ease of clarity only the mean is presented in the tables and figures, without reference to the standard deviation.

Differences in the duration of throwing and the distance thrown were assessed using Cohen's d statistic (Cohen 1988), with the pooled standard deviation being used as the denominator.

Cohen's d is an effect size used to show the difference between two means and is not influenced by sample size (Frohlich, Emrich, Pieter and Stark 2009). Effect size classification usually shows the following values: *small* effect (d = 0.20), *medium* effect (d = 0.50) and *large* effect (d = 0.80), as described by Cohen (1988).

4.1.3 Results

The majority of the reflective markers remained visible throughout the throwing action as shown by moving the Qualisys model throughout the whole throwing motion. The exception was the left ASIS which moved out of sight on a number of occasions during the forward movement prior to release. This may have been due to the excess abdominal mass often seen in those with lower spinal injury (Figure 4 3).

Although throwing duration was slightly longer (0.02 seconds, Cohen's d = 0.89) with the nearer pole position (Condition 2), there was little difference in the mean performances (0.02 m, Cohen's d = 0.06) for the two throwing configurations (Table 4 2). Importantly, despite a large effect size being returned for Condition 2, a difference in 0.02 seconds in human movement duration is extremely minimal. The effect size can almost be ignored as a consequence of the highly consistent duration of movements within each position (i.e. a very small pooled standard deviation). Although the effect size is minimal, the longer throwing distance needs to be considered as it would "win" the competition, even if by only 2 cm.

Table 4 2: Mean data for throwing configurations from Power to Release positions.

	Nearer Holding Pole position	**Further Holding Pole position**
Performance (m)	8.86 ± 0.34	8.84 ± 0.36
Time (s)	0.40 ± 0.03	0.38 ± 0.01

As mentioned previously, for ease of clarity only mean data will be presented in the tables and figures below. Differences in trunk rotation between Condition 1 and Condition 2 were seen in both the magnitude and the movement characteristics of the throwing action. There was a greater range of trunk motion generating a greater trunk angle for Condition 2 (Figure 4 6). Interestingly, the change from external to internal trunk rotation happened at the same time for both conditions, 0.25 s after the athlete moved out of the Power position (Table 4 3).

Table 4 3: Mean data breakdown for trunk angle (degs) for Conditions 1 and 2.

	Condition 1: Further pole position			**Condition 2: Nearer** pole position		
Event	**Onset t (s)**	**% of throwing duration**	**Angle (°)**	**Onset t (s)**	**% of throwing duration**	**Angle (°)**
Power	0	0	20.57	0	0	29.86
Release	0.38	100	-10.63	0.40	100	-28.85
Cross-over point	0.25	66	0	0.25	63	0
Range			35.60			58.71
Total time (s)	0.38			0.40		

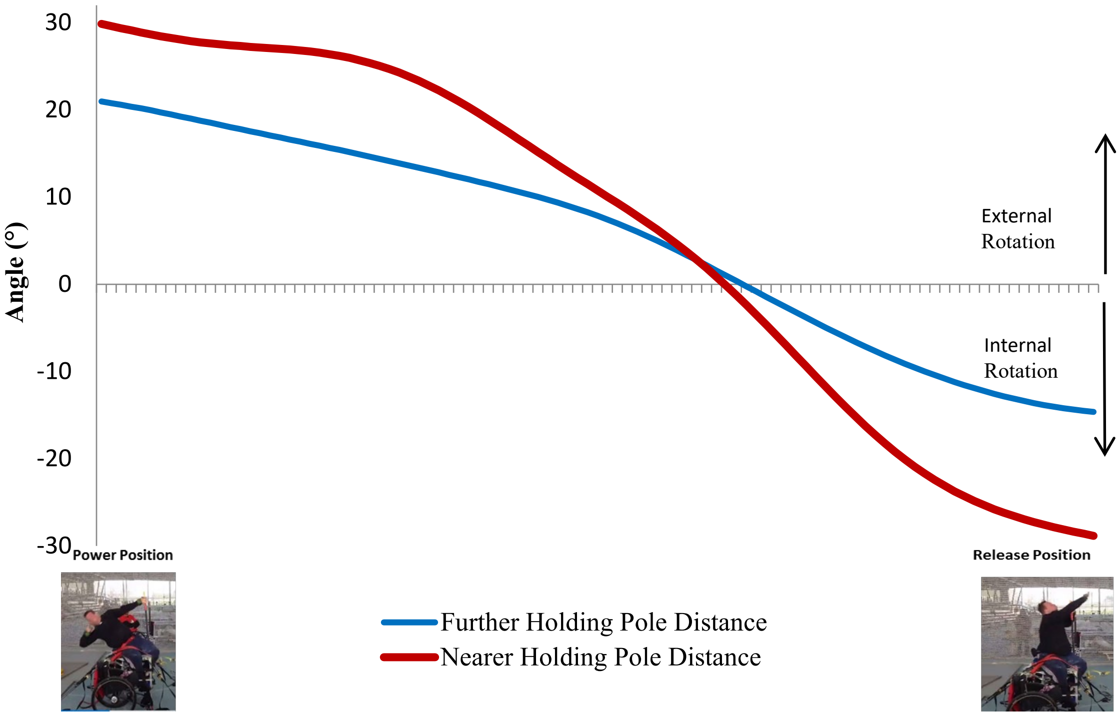


Figure 4 6: Mean progression of trunk angle from Power to Release positions (horizontal axis), over the throw time expressed in percentage of throwing time (%TT).

Table 4 4: Mean data breakdown for trunk angle (degs) for Conditions 1 and 2.

	Condition 1: Further pole position			**Condition 2: Nearer** pole position		
Event	**Onset t (s)**	**% of throwing duration**	**Angle (°)**	**Onset t (s)**	**% of throwing duration**	**Angle (°)**
Power	0	0	20.57	0	0	29.86
Release	0.38	100	-10.63	0.40	100	-28.85
Cross-over point	0.25	66	0	0.25	63	0
Range			35.60			58.71
Total time (s)	0.38			0.40		

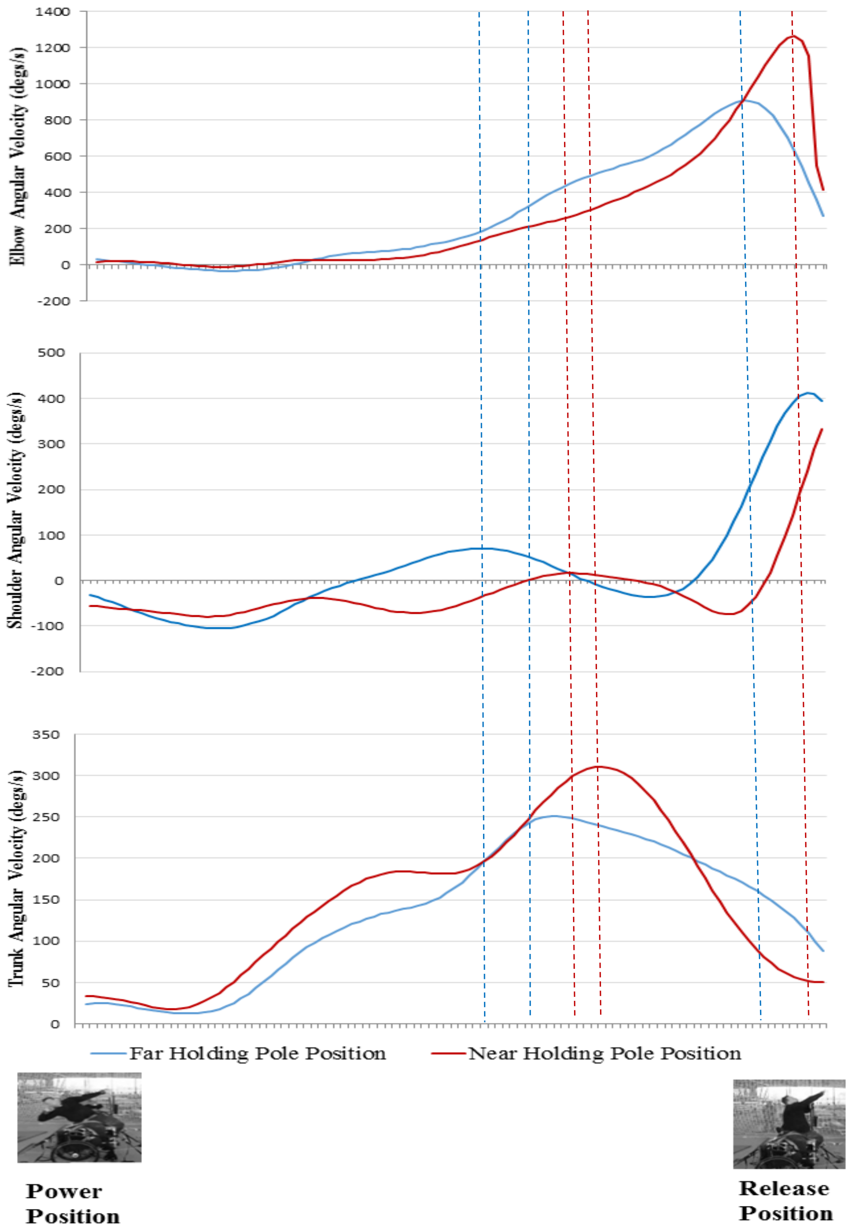


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Figure 4 7: Mean progression of trunk, shoulder and elbow angular velocities from Power to Release positions (horizontal axis) over the throw time expressed in percentage of throwing time (%TT), with dotted lines at velocity peaks demonstrating proximal-distal sequencing.

Table 4 5: Mean data breakdown of trunk angular velocity (degs/s) for Conditions 1 and 2, where P and T are peaks and troughs in the graph in order from power to release positions.

Condition 1: Further pole position				**Condition 2: Nearer** pole position			
Event	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**
Power	0	0	20.25	Power	0	0	33.56
T1	0.06	15	12.43	T1	0.05	13	18.04
P1	0.24	64	251.17	P1	0.18	44	183.84
P2				P2	0.20	50	181.33
T2				T2	0.28	71	310.93

Release	0.38	100	155.18	Release	0.40	100	81.21
Max	0.24	64	251.17	Max	0.28	71	310.93
Min	0.06	15	12.43	Min	0.05	13	18.04
Range			238.74	Range			292.89
Total Time (s)	0.38			Total Time (s)	0.40		

Table 4 6: Mean data breakdown of shoulder angular velocity (degs/s) for Conditions 1 and 2, where P and T are peaks and troughs in the graph in order from power to release positions.

Condition 1: Further pole position				**Condition 2: Nearer** pole position			
Event	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**
Power	0	0	-31.51	Power	0	0	-55.23
T1	0.06	17	-105.3	T1	0.06	16	-79.10
P1	0.20	53	70.93	P1	0.12	31	-37.84
P2	0.29	77	-35.88	P2	0.18	44	-70.67
T2				T2	0.27	67	16.13
P3				P3	0.35	88	-74
Release	0.38	100	405.83	Release	0.40	100	288.25
Max	0.37	98	412.57	Max	0.40	100	288.25
Min	0.06	17	-105.34	Min	0.06	16	-79.10
Range			517.91	Range			367.35
Total Time (s)	0.38			Total Time (s)	0.40		

Table 4 7: Mean data breakdown of elbow angular velocity (degs/s) for Conditions 1 and 2, where P and T are peaks and troughs in the graph in order from power to release positions.

Condition 1: Further pole position				**Condition 2: Nearer** pole position			
Event	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throw duration**	**Angular velocity (°/s)**
Power	0	0	-31.51	Power	0	0	-55.23
T1	0.06	17	-105.3	T1	0.06	16	-79.10
P1	0.20	53	70.93	P1	0.12	31	-37.84
P2	0.29	77	-35.88	P2	0.18	44	-70.67
T2				T2	0.27	67	16.13
P3				P3	0.35	88	-74
Release	0.38	100	405.83	Release	0.40	100	288.25
Max	0.37	98	412.57	Max	0.40	100	288.25
Min	0.06	17	-105.34	Min	0.06	16	-79.10
Range				Range			
Total Time (s)			0.38	Total Time (s)			0.40

Movement pattern sequencing is the order in which body segments move, sometimes referring to proximal-distal sequencing. The expected order of trunk, shoulder, elbow is as suggested by other throwing related research (Urbin, Fleisig, Abebe and Andrews 2013; Wagner, Pfusterschmied, Tilp, Landlinger, Duvillard and Müller 2014). The proximal-distal sequencing is defined by the onset sequencing of the velocity peaks, as shown in Table 4 8 and Figure 4 7. The maximal angular velocity values were in the expected order of magnitude for trunk, shoulder, elbow for Condition 1. However, the sequence was throwing shoulder, trunk, elbow for Condition 2. In terms of timing of the maximal angular velocities the order was trunk, elbow, shoulder, for both conditions.

Table 4 8: Proximal – distal sequencing of trunk, shoulder and elbow angular velocities.

	Condition 1: Further pole position		**Condition 2: Nearer** pole position	
	time (s)	**Peak Angular Velocity** (degs/s)	**time (s)**	**Peak Angular Velocity** (degs/s)
Trunk	0.24	251.17	0.28	310.93
Shoulder	0.37	412.57	0.40	288.25
Elbow	0.34	907.29	0.38	1260.90

4.1.4 Discussion

Set-up Design Protocols

As mentioned, the majority of reflective markers remained visible at all times throughout the throwing movement. However, the ASIS markers often went out of view, particularly when close to the release point. This may be due to the classification of the athlete, consistent with lower spinal dysfunction resulting in excess lower abdominal fat covering the marker at certain parts of the throwing movement, especially when the athlete is transitioning from hip extension to flexion. This would be further affected by being in a seated position. As the ASIS markers are required to create the pelvis in Visual 3D it is essential that they remain visible throughout the movement.

Holding Pole Positioning

Holding pole position changed the movement characteristics and thus throwing technique/co-ordination strategy. The greatest differences were seen in trunk and elbow angular velocity for Condition 1. Both variables displayed greater maximum angular velocities from the power to release positions, than those of Condition 2. Although acceleration was not measured independently, it can be viewed by looking at the change in velocity between the power and release positions (Figure 4 7).

Trunk angular velocity, also referred to as trunk whip in other throwing activity and the x-factor in sports such as golf (Joyce, Burnett, Cochrane, Ball and Ball 2010), is thought to positively influence trunk muscle stretch, producing greater force and promoting muscle contraction (Judge, Young and Wanless 2011). It should be as large as possible when the athlete is just exiting the power position (Bartoniez and Borgstöm 1995, Young and Li 2005). Trunk whip is likely to be even more critical to performance for a seated athlete as the legs are unable to be used during the throwing action.

Trunk whip is also likely to be influenced by throwing characteristics such as athlete's seating direction, whether they use a holding pole, and how the athlete is secured to their throwing frame (Tweedy, Connick, Burkett, Sayers, Meyer and Vanlandewijck 2012). Similarly, the maximum elbow angular velocity (throwing arm) was also greater for the nearer holding pole position.

Holding pole positioning positively influenced movement characteristics of the trunk, in particular, trunk rotation and trunk angular velocity. Both of these variables have been shown to positively influence performance (Bartoniez and Borgstöm 1995, Young and Li 2005). Trunk movement maybe an important characteristic that athletes and coaches need to consider for throwing technique and when designing a throwing frame.

The athlete used in this study currently throws using the further holding pole position. The greater trunk range and angular velocity, and slightly better performance for the nearer holding pole position maybe something the athlete and coach would want to consider. It is likely that movement pattern sequencing is different so spending time on developing this further could positively influence performance. More biomechanical analysis of the influence of such characteristics is necessary so coaches can make evidenced based decisions on the throwing technique for seated throwers.

Limitations

Due to similarities between Study 1A and 1B, limitations for both studies will be discussed together and presented at the end of Study 1B discussion.

4.1.5 Conclusion

As a consequence of the findings from Study 1A, and to avoid similar issues in the future the following interventions will be implemented for the next study:

- larger ASIS markers will be used
- the number of cameras used will be increased from ten to twenty.

4.2 Study 1B - Further exploration of methodological protocols for 3D kinematic analysis of seated shot-putters.

4.2.1 Introduction

Study 1B naturally progressed from Study 1A with the view that the recommendations would be implemented from this first study. These included using larger ASIS markers and increasing the number of 3D cameras. Additionally, seating configuration (sitting direction and use of holding pole) was explored.

Purposes

The main purpose of Study 1B was to investigate how throwing technique, including onset of key events between the power and release positions, are affected by four different throwing configurations, which involved:

- different sitting directions (front on or diagonal)
- the use of a holding pole (with or without holding pole), as shown Figure 4 8.

4.2.2 Methods

Participants

One female elite level Class F34 right-handed shot-putter participated in the study (Age 39 years, Height 1.69 m, Mass 90.3 kg). Standard informed consent procedure was followed in accordance with the ethical approval given by the Middlesex University LSI Ethics Committee (Appendix A1). At the time of testing, she was the only elite level athlete in this class in the UK.

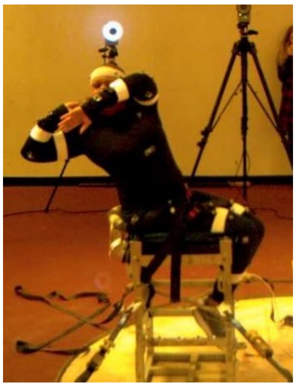
	Front On both knees facing forward	**Diagonal** left knee facing forward, right knee facing diagonal to the side
With Holding Pole	 **Seating Configuration A**	 **Seating Configuration B**
Without Holding Pole	 **Seating Configuration C**	 **Seating Configuration D**

Figure 4 8:Throwing Configurations A, B, C, D - Front On and Diagonal with and without holding pole.

The in-lab testing was aligned to in-competition conditions as much as possible. Thus, the participant was required to throw six maximal throws (as in a competition) for each throwing configuration during a single testing session. The throwing configurations were referred to as Seating Configurations A to D, described as follows (Figure 4 8);

- **Seating Configuration A** - front on sitting position using a holding pole
- **Seating Configuration B** - diagonal on sitting position using a holding pole
- **Seating Configuration C** - front on sitting position without a holding pole
- **Seating Configuration D** - diagonal on sitting position without a holding pole.

Apparatus

The participant also threw from her own throwing frame which complied with World Para Athletics rules governing throwing frame specifications (WPA 2020 – 2021). The throwing frame was secured to the ground using ratchet straps from each corner of the frame into purpose-built eye bolts set into the floor (Figure 4 2). The personal throwing frame had only one position for the holding pole which was used throughout the testing when needed.

Recording

The number and locations for the reflective marker placement was replicated from Study 1A (Table 4 1) except that larger markers were placed on left and right ASIS positions, as recommended. The participant was asked to hold a stationary position for five seconds which was captured by the cameras. This was to create a static model, as described previously. After conducting her usual competition warm-up, the participant was asked to throw six maximal throws from the four different throwing configurations (Figure 4 8). Thus, the total number of trials was n = 24. Distance thrown was manually measured and recorded after each trial. The data collection protocol was the same as for Study 1A except that the number of cameras was increased from 10 to 20, as recommended, and equally spaced around the testing equipment.

Processing

Based on the results from Study 1A and in line with previous research of shot-put, other throwing activities involving non-disabled participants (Bartoniez and Borgstöm 1995; Young and Li 2005; Young and Wanless 2011), it was decided to continue with the same kinematic variables previously selected and to also include the wrist angular velocity. Thus, the following variables were:

- Trunk angle
- Angular velocity of trunk, shoulder, elbow, wrist.

The throwing movement was broken down into the same two positions as for Study 1A, namely the Power and Release positions as described previously in Figure 4 5 and Figure 4 8. The mean of the six trials was used for analysis, trunk angle and joint angular velocities were time normalised to facilitate averaging of datasets and to allow comparison between the configurations.

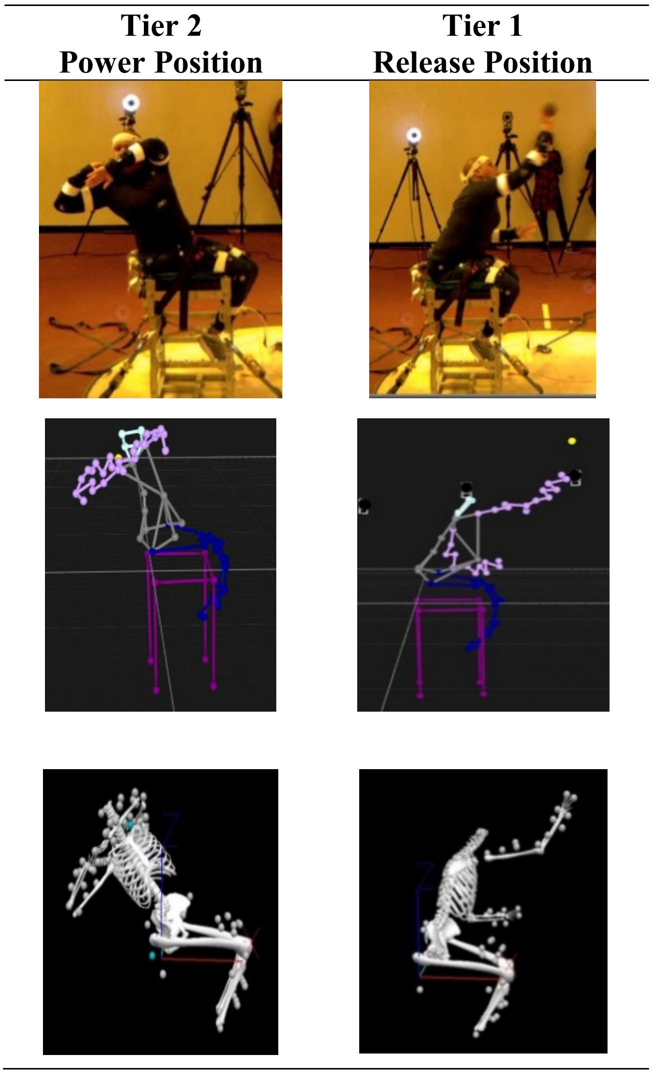


Figure 4 9: Example of Power and Release position visuals using Qualisys and Visual 3D software.

4.2.3 Results

Throwing duration was longer for the throwing Configurations C and D than Configurations A and B. However, the throwing configuration that had the shortest time duration between Power and Release positions (Configuration A - 0.38 s ± 0.01) did not bring about the best performance (Table 4 9). Seating Configuration C recorded the longest mean performance.

Table 4 9: Mean data for throwing configurations from power to release positions.

	Seating Configuration A **Front On** with holding pole	Seating Configuration B **Diagonal** with holding pole	Seating Configuration C **Front On** without holding pole	Seating Configuration D **Diagonal** without holding pole
Performance (m)	6.48 ± 0.24	6.23 ± 0.28	6.93 ± 0.17	6.26 ± 0.24
Time (s)	0.38 ± 0.01	0.41 ± 0.04	0.55 ± 0.03	0.61 ± 0.02

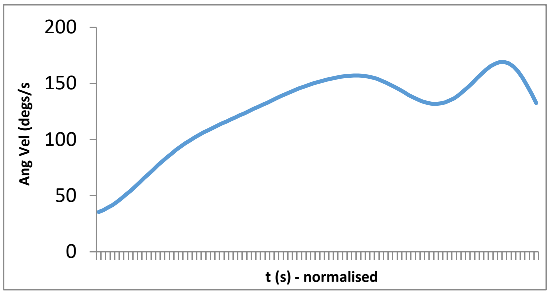
Differences in the movement characteristics between the four different throwing configurations for joint angular velocities (trunk, shoulder, elbow and wrist) are shown in Figure 4 10. There appears to be two different movement pattern clusters with some similarities between Conditions A and B, with a holding pole, and between Conditions C and D, without a holding pole (Figure 4 10), for the former three variables. The movement characteristics for wrist angular velocity are less obvious. Movement pattern sequencing, here referring to proximal-distal sequencing, refers to the order in which body segments move. The order, as suggested by other throwing related research (Urbin, Fleisig, Abebe and Andrews 2013; Wagner, Pfusterschmied, Tilp, Landlinger, von Duvillard and Müller 2014), should be trunk, shoulder, elbow, wrist. This does not appear to be the case here with the maximal trunk and shoulder angular velocities occurring concurrently.

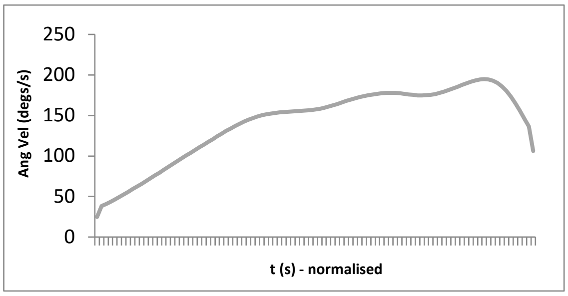
Trunk Angular Velocity

The two throwing configurations with a holding pole (Configurations A and B) show similar movement patterns especially towards the earlier part of the throwing pattern i.e. out of the power position. The slope of the graph in each case is mostly level out of the power phase, suggesting a movement with a rather constant angular velocity. There is a small difference heading into the release with the front on sitting position (Configuration A) exhibiting a decrease in trunk angular velocity before another increase suggesting a final acceleration into the release. However, the diagonal sitting position (Configuration B) exhibits a larger maximal trunk angular velocity of the two conditions (190.87 for B to 169.16 degs/s for A).

Table 4 10: Mean data breakdown of trunk angular velocity (degs/s) for Seating Configurations A and B, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration A: **Front On** with holding pole				**Configuration B:** **Diagonal On** with holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.001	2	35.44	Power	0.004	1	20.73
P1	0.22	58	157.02	P1	0.36	89	190.87
T1	0.29	76	131.82	T1			
P2	0.35	91	169.16	P2			
Release	100	100	132.66	Release	0.41	100	105.97



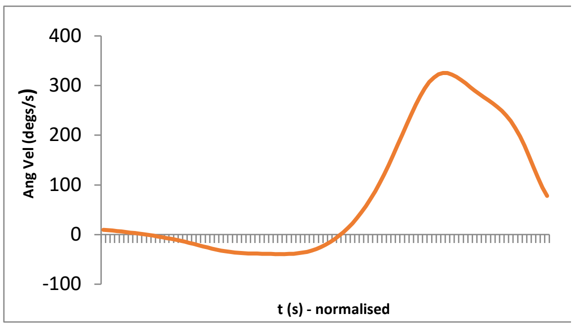


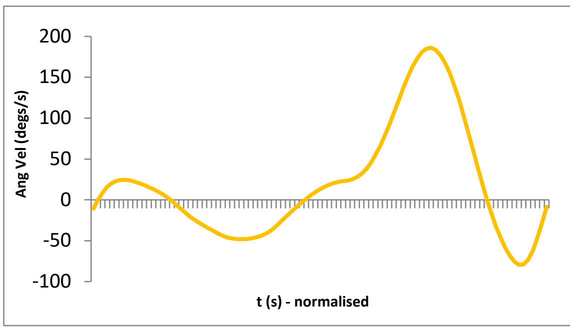
Max	0.35	91	169.16	Max	0.36	89	190.87
Min	0.01	2	35.44	Min	0.004	1	20.73
Range			200.60	Range			219.60
Total Time (s)	0.38			Total Time (s)	0.41		

The two throwing configurations without holding pole (Configurations C and D - Table 4 11) displayed differences in movement pattern to the with holding pole throwing configurations (Configurations A and B – Figure 4 10). They also displayed differences between each other, with Configuration C having a greater range (difference between minimum and maximum values) of trunk angular velocity (360.79 degs/s) resulting in a steeper and more direct pathway into the release point, shown by the slope (Table 4 11). It also has a larger maximal trunk angular velocity (325.4 degs/s) of the four throwing configurations.

Table 4 11: Mean data breakdown of trunk angular velocity (degs/s) for Seating Configurations C and D, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration C: Front On without holding pole				**Configuration D: Diagonal On** without holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.006	1	9.75	Power	-10.92	1	0.006
T1	0.22	40	-39.39	P1	20.28	8	0.05
P1	0.42	76	325.4	T1	-48.24	33	0.20
P2				P2	186.18	74	0.44
T2	0.55			T2	-79.59	93	0.57
Release		100	77.30	Release	-8.59	100	0.61





Max	0.42	76	325.4	Max	0.44	74	186.18
Min	0.22	40	-39.39	Min	0.57	93	-79.59
Range			360.79	Range			265.77
Total Time (s)	0.55			Total Time (s)	0.61		

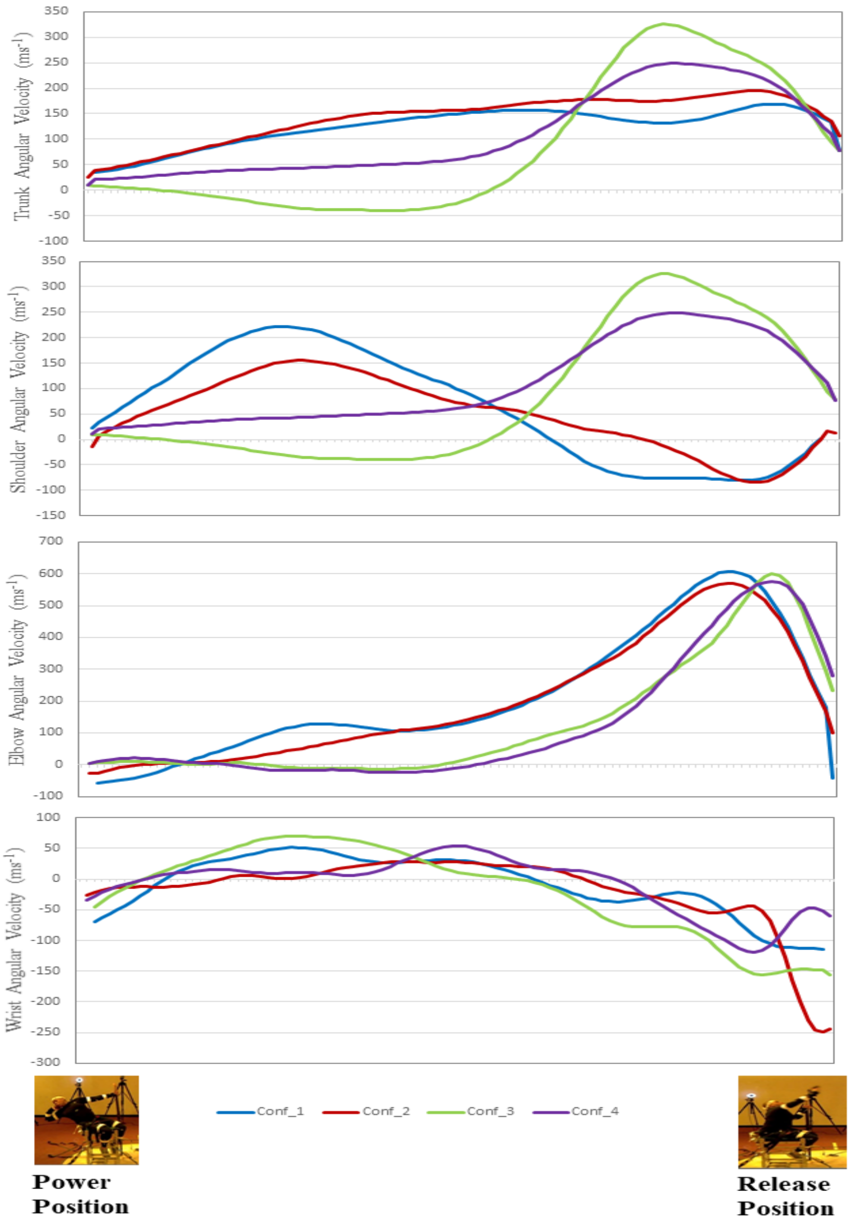


Figure 4 10: Mean angular velocity of Trunk, Shoulder, Elbow and Wrist. over the throw time expressed in percentage of throwing time (%TT).

Shoulder Angular Velocity

As with trunk angular velocity there are two different movement pattern clusters with some intra similarities between Configurations A and B (with holding pole) and Configurations C and D (without holding pole) as shown in Figure 4 10, Table 4 12 and Table 4 13.

The with holding pole seating Configurations (A and B – Table 4 12) have larger angular accelerations (shown by the slope of the graph) out of the Power position before slowing down heading into the release point, with the front on seating configuration (Configuration A) displaying a greater range of angular velocity and a greater deceleration.

Seating Configurations C and D (without holding pole) display the opposite movement pattern with greater acceleration into the release point (Table 4 13). The front on with no holding pole position (Configuration C) has the greatest maximal angular shoulder velocity (221.81 degs/s) and range (302.3 degs/s) of the four throwing configurations.

Table 4 12: Mean data breakdown of shoulder angular velocity (degs/s) for Configurations A and B, where P and T are peaks and troughs in the graph in order from power to release positions.

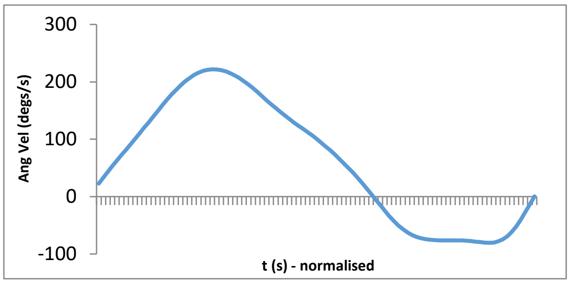
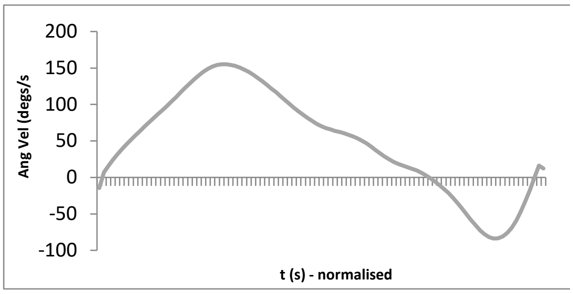
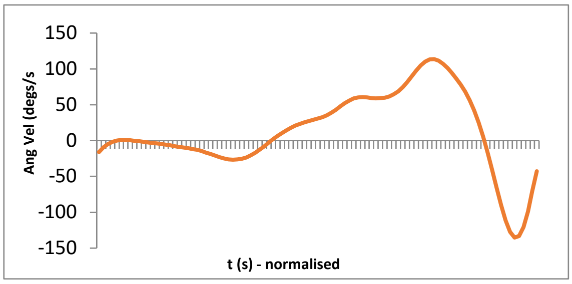
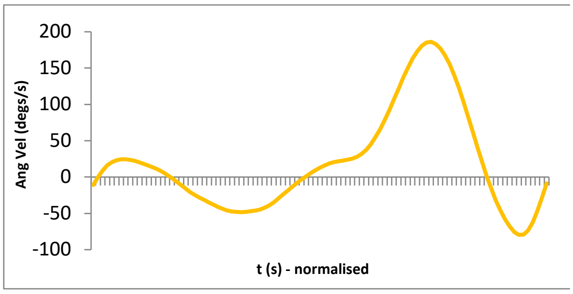
Configuration A: **Front On** with holding pole				**Configuration B:** **Diagonal On** with holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.004	1	22.87	Power	0.004	1	-10.49
P1	0.10	26	221.80	P1	0.12	29	155.09
T1	0.33	88	-80.51	T1	0.36	89	-83.78
P2				P2			
T2				T2			
Release	0.38	100	0.35	Release	0.41	100	12.46
							
Max	0.10	26	221.81	Max	0.12	29	155.11
Min	0.33	88	-80.51	Min	0.36	89	-83.78
Range			302.32	Range			238.89
Total Time (s)	0.38			Total Time (s)	0.41		

Table 4 13: Mean data breakdown of shoulder angular velocity (degs/s).for Configurations C and D, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration C: **Front On** without holding pole				**Configuration D:** **Diagonal On** without holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**

Power	0.006	1	-15.80	Power	0.006	1	-10.92
P1	0.04	7	0.98	P1	0.05	8	20.28
T1	0.17	31	-26.59	T1	0.20	33	-48.24
P2	0.41	75	113.66	P2	0.44	74	186.18
T2	0.52	94	-135.27	T2	0.57	93	-79.59
Release	0.55	100	-42.55	Release	0.61	100	-8.59





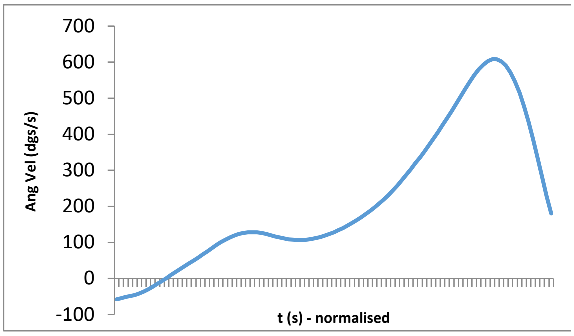
Max	0.41	75	113.66	Max	0.44	74	186.18
Min	0.52	94	-135.27	Min	0.57	93	-79.59
Range			248.93	Range			265.77
Total Time (s)	0.55			Total Time (s)	0.61		

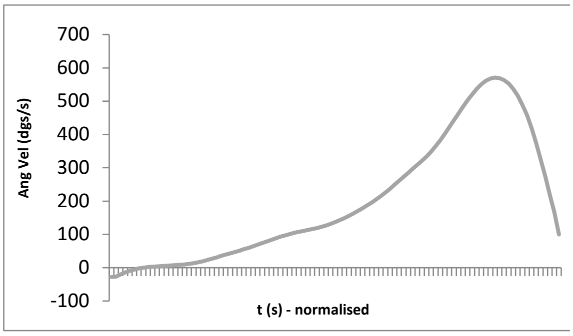
Elbow Angular Velocity

For elbow angular velocity, two movement clusters are very evident and the general movement pathway for all configurations (A – D, with and without holding pole) are similar. Similar maximal elbow angular velocity (between 570.72 and 607.97 degs/s) is experienced for all conditions, although the without holding pole seating configurations have a slightly steeper gradient and reach maximal angular elbow velocity closer to the release point (Table 4 15).

Table 4 14: Mean data breakdown of elbow angular velocity (degs/s) for Configurations A and B, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration A: **Front On** with holding pole				**Configuration B:** **Diagonal On** with holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.004	1	-57.64	Power	0.006	1	0.05
P1	0.12	31	128.52	P1	0.004	1	-27.97
T1	0.16	43	107.69	T1	0.35	86	570.72
P2	0.32	85	607.94	P2			
Release	0.38	100	180.16	Release	0.41	100	99.39



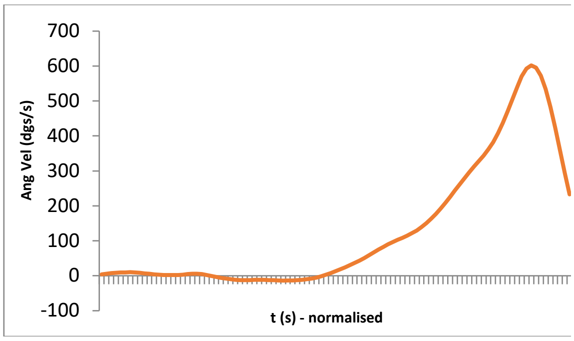


Max	0.32	85	607.94	Max	155.11	86	570.72
Min	0.004	1	-57.64	Min	-83.78	1	-27.97
Range			665.58	Range	238.89		598.69
Total Time (s)	0.38			Total Time (s)	155.11		

Table 4 15: Mean data breakdown of elbow angular velocity (degs/s) for Configurations C and D, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration C:
Front On without holding pole

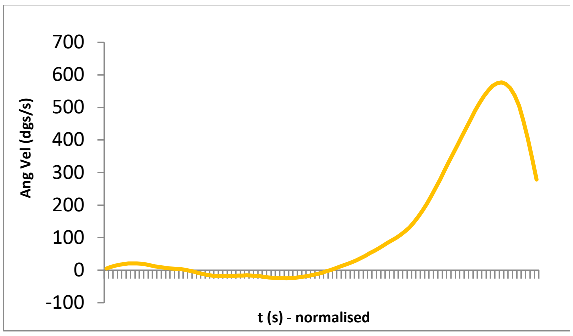
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.006	1	0.05
P1	0.04	7	10.01
T1	0.09	15	1.72
P2	0.12	21	5.64
T2	0.17	31	-12.38
P3	0.19	34	-11.37
T3	0.23	41	-13.93
P4	0.51	92	601.94
Release	0.55	100	233.02



Max	0.51	92	601.94
Min	0.23	41	-13.83
Range			615.77
Total Time (s)	0.55		

Configuration D:
Diagonal On without holding pole

Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.006	1	0.57
P1	0.04	7	21.00
T1	0.26	42	-20.95
P2	0.56	92	577.08
T2			
P3			
T3			
P4			
Release	0.61	100	278.29



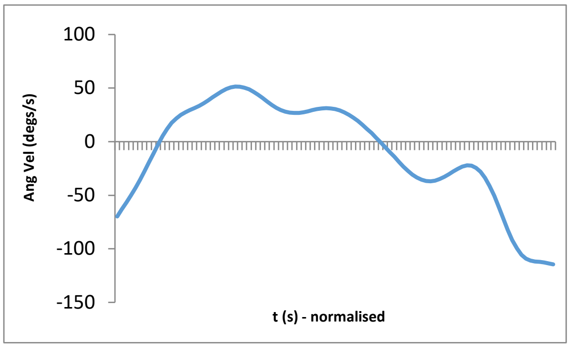
Max	0.56	92	577.08
Min	0.26	42	-20.95
Range			602.03
Total Time (s)	0.61		

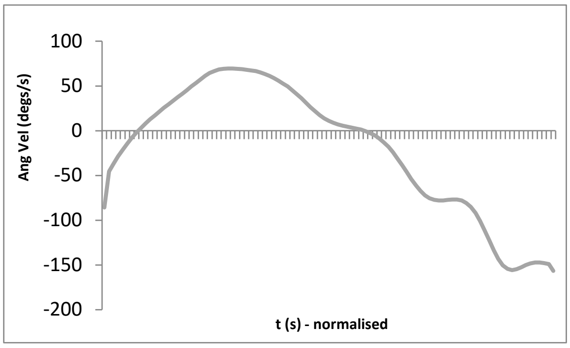
Wrist Angular Velocity

Differences between the movement patterns of the seating configurations with regards to wrist angular velocity are less defined. The front on without holding pole (Configuration C) displays the greatest deceleration into the release, whilst the diagonal without holding pole (Configuration D) exhibits a steeper velocity into the release (Table 4 17).

Table 4 16: Mean data breakdown of wrsit angular velocity (degs/s) for Configurations A and B, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration A: **Front On** with holding pole				**Configuration B:** **Diagonal On** with holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.004	1	-69.79	Power	0.004	1	-85.68
P1	0.11	27	51.44	P1	0.11	28	69.45
T1	0.15	40	26.73	T1	0.30	74	-78.07
P2	0.18	47	31.26	P2	0.32	78	-76.93
T2	0.27	70	-37.02	T2	0.38	90	-155.75
P3	0.30	79	-22.45	P3	0.40	97	-147.92
Release	0.38	100	-110.50	Release	0.41	100	-156.64



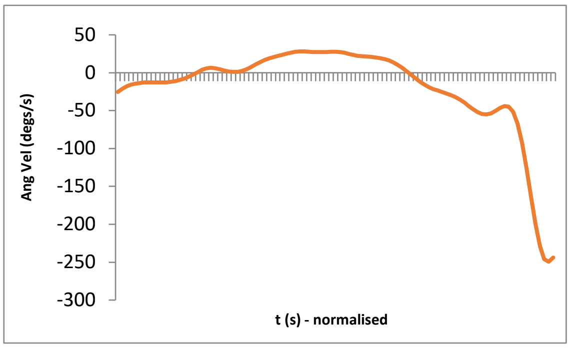


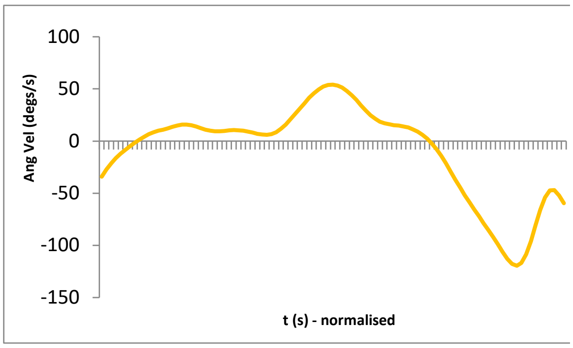
Event	Onset t (s)	% of throwing duration	Angular velocity (°/s)	Event	Onset t (s)	% of throwing duration	Angular velocity (°/s)
Max	0.11	27	51.44	Max	0.11	28	69.45
Min	0.38	100	-110.50	Min	0.41	100	-156.64
Range			165.94	Range			226.09
Total Time (s)	0.38			Total Time (s)	0.41		

Table 4 17: Mean data breakdown of Wrist angular velocity (degs/s) for Conditions C and D, where P and T are peaks and troughs in the graph in order from power to release positions.

Configuration C: **Front On** without holding pole				**Configuration D:** **Diagonal On** without holding pole			
Event	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**	**Event**	**Onset t (s)**	**% of throwing duration**	**Angular velocity (°/s)**
Power	0.006	1	-25.56	Power	0.006	1	-30.16
P1	0.12	22	6.46	P1	0.11	18	15.73

T1	0.15	27	1.10	T1	0.22	36	5.94
P2	0.24	43	28.21	P2	0.31	50	50.12
T2	0.46	84	-50.94	T2	0.54	88	-119.30
P3	0.49	89	-40.63	P3	0.59	96	-47.15
Release	0.55	100	243.97	Release	0.61	100	-59.07





Max	0.24	43	28.21	Max	0.31	50	50.12
Min	0.55	100	-243.97	Min	0.54	88	-119.30
Range			272.18	Range			173.42
Total Time (s)	0.55			Total Time (s)	0.61		

4.2.4 Discussion

This is the first study to investigate seating configurations for elite seated shot-putters.

Set-up Design Protocols

The majority of reflective markers remained visible at all times throughout the throwing movement. The changes made based on Study 1A recommendations improved the tracking of the ASIS marker. This may also have been due to the different classification of the participant, having greater spinal function resulting in less abdominal fat covering the ASIS marker at parts of the throwing movement. In accordance with the recommendations from Study 1A the number of infra-red cameras had been increased from 10 to 20 and this may have also played a part in this.

Seating Configuration

Seating direction and use of holding pole changed the movement pattern and thus throwing technique. The use of holding pole (Configurations A and B) as a variable produced similar between configuration movement patterns. The seating configurations without a holding pole (Configurations C and D) produced the higher angular velocities for trunk, shoulder and elbow prior to release, and steeper velocity leading into the release.

The data from this feasibility study and for this participant, is suggesting that performance may be positively influenced when a holding pole is not used. This contrasts with the findings of Burkett, Connick, Sayers, Hogarth, Stevens, Hurkx and Tweedy (2016) who found no differences between with or without holding pole, in a non-disabled population. This highlights the importance of considering similar and relevant populations for research. Lesser variations were shown between the front on and diagonal on sitting positions.

The seating configuration that produced the greatest trunk angular velocity and steepest velocity into the release was seating Configuration C (diagonal on without holding pole). This seating configuration also produced the best performance. This participant usual uses a different throwing configuration, Configuration A (front on with holding pole), and this may have impacted on the performance along with the athlete's limited training history. It is likely that movement pattern sequencing and timing is different between the configurations, so spending time on developing this further might positively influence performance for this participant. The data provided by this study could be useful to coaches and athletes when deciding what the favourable seated configuration might be to improve performance.

Limitations specific to Study 1A and Study 1B

As Studies 1A and 1B were both single case studies, the limitations for both will be presented together here. Only one participant from one impairment class was used in each of the studies. Thus, the results relate only to these participants, and the data cannot be used to inform any inter-participant variability. Future studies including a greater number of athletes from the same functional class and also those with a variety of classifications would help to understand how this constraint might impact on performance.

Functional level and throwing frame have been identified as organism-led constraints within a co-ordination strategy (Keogh 2011; Keogh and Burkett 2016). The participants in these feasibility studies used their own throwing frames. This could impact results by negating this organism-led constraint through an already established co-ordination strategy, developed through time spent in-training and in-competition. In future studies, implementing the use of a generic, adjustable throwing frame might increase the impact of the throwing frame as an organism-led constraint. To expose the impact of throwing frame as a constraint, it was important to conduct further studies focusing on different sitting positions, with and without the use of a holding pole using a generic throwing frame that all participants would use. These recommendations were employed in the subsequent studies.

The only statistics used to consider differences between holding pole positions in Study 1A was Cohen's d.

4.2.5 Conclusion

As a consequence of the findings from Study 1B, the following interventions will be implemented for the next study:

- larger ASIS markers will be used
- a 20-camera set-up will be utilised for data capture purposes
- the four seating configurations to be considered will be:
  - Front on with holding pole
  - Diagonal on with holding pole
  - Front on without holding pole
  - Diagonal on without holding pole.

Due to the minimal differences between the seating configurations for wrist angular velocity (Figure 4 10), it was decided that a shot-put/hand segment would be considered for the subsequent studies. This was deemed relevant as it is the outcome of the shot-put movement that ultimately determines performance.

The results provided insight to inform the following studies (1C, 2 and 3) with regards to design protocols, selection of seating configurations and the capacity to measure variable differences. It also provided information to the individual participants and their coach for consideration, with regards to preferred seating configuration.

4.3 Study 1C - Calculation of performance: An Error Analysis

Introduction

The outcome of elite seated shot-putters at major competitions, such as the Paralympic Games, is determined on how far the athlete is able to throw the shot-put. Athletes are given six opportunities to throw during competition, but it is the longest one that is compared with their competitors. The athlete with the longest throw of all athletes is the winner and takes the Gold medal.

Seated shot-putters use a bespoke throwing frame to train and compete. As explained in Chapter 2, each individual throwing frame must comply with the rules of the sport (WPA 2020 - 21), and current rules impose many more constraints than previously (Table 2 2). The interaction between the design of the throwing frame and throwing technique, depending on the athlete's physical capacities, is paramount to the performance. This interaction influences the release parameters of the shot-put trajectory (O'Riordan and Frossard 2006; Frossard, Smeathers Evans, O'Riordan and Goodman 2008). Shot-put release parameters, including the velocity, angle and height of release, has been studied closely over the years, both for standing (Dessurealt 1978; Lichtenburg and Wills 1978; Ariel 1979; Linthorne 2001) and seated (Chow, Chae and Crawford 2000; Frossard, O'Riordan, Goodman and Smeathers 2005; Frossard, O'Riordan and Goodman 2005, 2007) shot-put.

Flight Characteristics of the Shot-put

The horizontal displacement of a projectile can be represented by the following equation:

$$P = \frac{Vox}{g}\left(Voz + \sqrt{Voz^2 + 2 * Zo * g}\right)$$

Where,
P = the horizontal displacement (calculated throwing distance), i.e. performance
Z_0 = the height of release (A)
V_{ox} = the release velocity on the horizontal axis (D)
V_{oz} = the release velocity on the vertical axis (E)
G = acceleration due to gravity.

When the shot-put is released, its horizontal displacement (the performance), as shown in Figure 4 11, is dependent on the release height (A), and release velocity (D in the horizontal direction and E in the vertical direction), often referred to as the projected distance and makes up 97% of the measured distance (Young and Li 2005). However, the horizontal distance that the release point is ahead of (or behind) the line of measurement needs to be included into the final calculation for the performance. This additional distance is referred to as the release gain in this thesis and is shown in Figure 4 11.

Release parameters can be determined using tri-dimensional motion capture and analysis software such as Qualisys and Visual 3D, respectively. Analysis of the release parameters rely heavily on the sampling frequency of 3D capture which might influence the identification of the point of release and the number of frames to consider around the time of release.

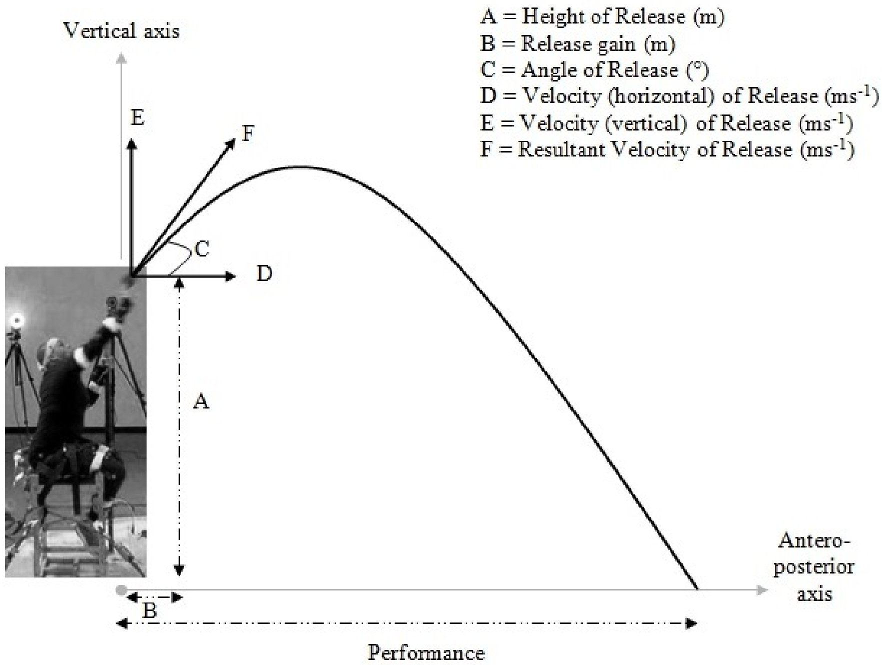


Figure 4 11: Definition of the parameters of the trajectory for seated shot-put. Performance is the horizontal displacement from the front of the throwing circle to the landing position of the shot-put. Flight distance is dependent on the release characteristics plus the release gain (the horizontal displacement between the front of the throwing circle and the release point).

Typically, as data collection and analysis software improve, researchers often rely too much on the basic theoretical principle where a change in time (Δt) is required to be able to calculate the release variables. The magnitude of Δt, and how different Δt values impact on the calculations is often overlooked. The software that implements basically the equations of aerial trajectory are frequently blindly trusted.

It is important to remember that when investigating release parameters, at least two points are needed to calculate velocity at release. Thus, of particular interest are differences between distances travelled during the flight trajectory and how this might impact on the accuracy of the release parameters. Here, accuracy or measurement error corresponded to the difference between the calculated and the measured performances.

There is limited research to direct this aspect of informing the distances travelled during the flight trajectory. However, one study did consider different flight trajectories of elite seated shot-putters and was able to make recommendations on how to improve the recording rate through a number of interventions including selecting the point of release and calculating the release parameters (Frossard, Smeathers, Evans, O'Riordan and Goodman 2008). A quality control procedure was developed which has been implemented in other studies (Tweedy, Connick, Sayers, Burkett et al. 2012; Hyde, Hogarth, Sayers, Beckman et al. 2016).

Thus, it is important to conduct a quality control process in this study as it will improve accuracy of the results by reducing differences between calculated and the manually measured performances, and ultimately improve overall thoroughness of biomechanical analysis of throwing technique.

Therefore, it is anticipated that this study will highlight the importance of:

- accurately determining important instances such as the point of release and distances travelled during the flight trajectory
- reporting outcomes considering both error and calculated quality
- conducting a quality control process when considering flight trajectory.

Aim

The aim of this study was to report and reduce the measurement error associated with the release parameters of seated shot-putters, based on different flight trajectories post release.

Objectives

The specific objectives of this study were to:

- present the release variables for different flight trajectories of the shot-put
- calculate the performance based on the release variables
- compare the calculated and measured performances
- assess the error of the calculated to measured performances comparison
- suggest a quality control procedure to improve accuracy.

4.3.1 Methods

The experimental set-up as well as data capture and processing used in this study has been detailed in Studies 1A and 1B. Therefore, only a brief description of key information will be presented here. This section will provide the typical information to include in the methods section of subsequent articles. The procedure of data collection and processing is shown in Figure 4 12.

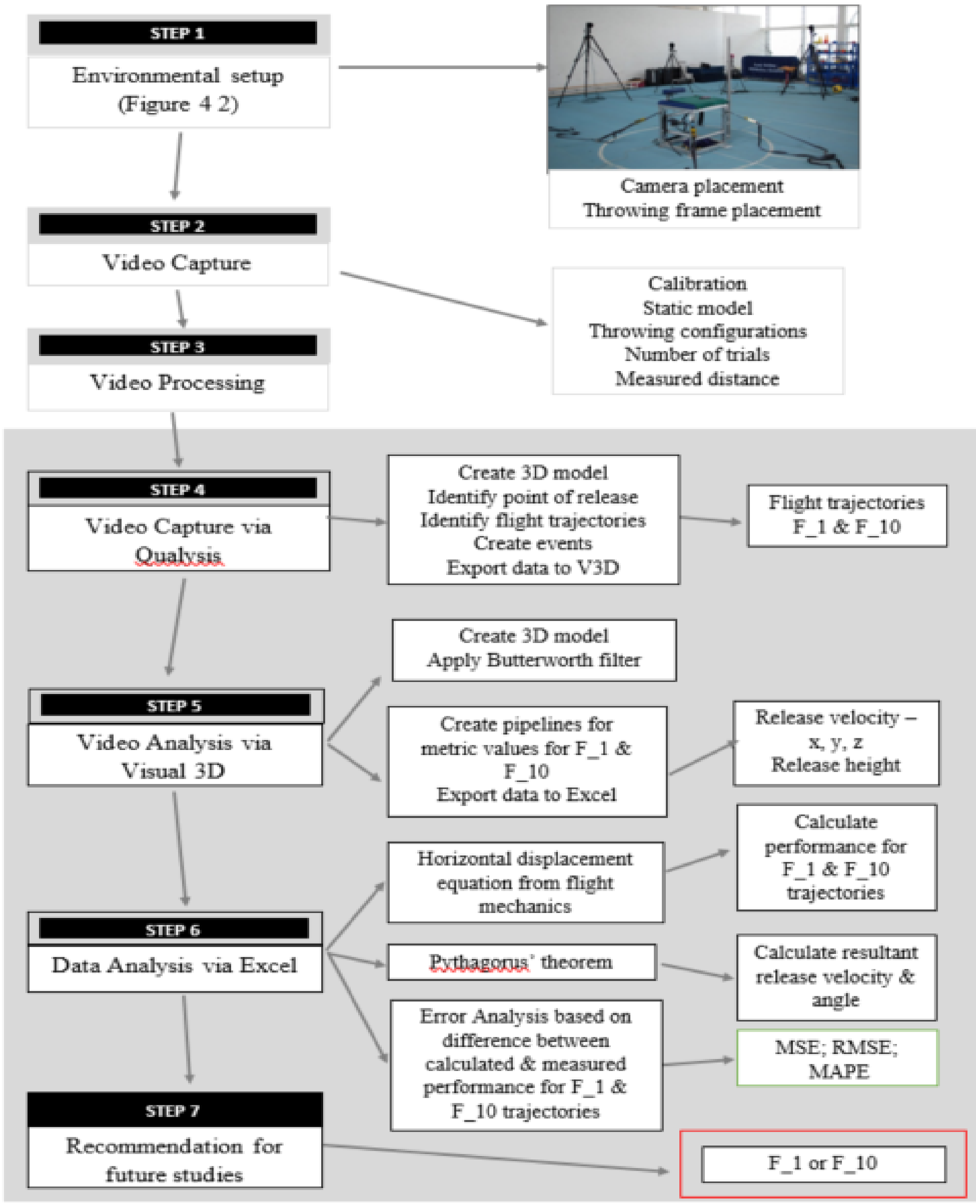


Figure 4 12: Seven key steps of data collection and processing used to determine flight variables and performance.

Participants

The World Para Athletics (WPA) World Championships were held in London in July 2017. This was seen as a unique opportunity to access world class seated shot-putters to be involved in this research. Using the 2017 WPA minimum qualification standard (MQS) rankings all seated shot-putters ranked in the World top ten in classes F55 to F57 were identified. The competition schedule was reviewed to identify a testing day that was after the seated shot-put events for males and females, and before the athletes flew home. There was only one day that this could happen, Saturday 17 July 2017. An invitation was sent via the National Paralympic Committees (NPCs) of the athletes (Appendix B 1). It was also promoted by The International Paralympic Committee (IPC) and via social media. A charity provided accessible transport to transfer the athletes from Olympic Park to the testing venue. This was a unique opportunity for a collective of world class para athletes to participate in applied research.

Eight elite level Class F55 (n = 3) and F56 (n = 5) seated shot-putters from various nations (37 ±10 years, 1.79 ±0.18 m, 95.33 ±26.02 kg) participated in the study. This cohort represented 23% of the total population of World Class seated shot-putters. Standard informed consent procedure was followed in accordance with the ethical approval given by the Middlesex University LSI Ethics Committee (Appendix A). All participants provided written consent.

Apparatus

a) Experimental throwing frame

Based on recommendations from Study 1A and Study 1B, participants threw from an experimental throwing frame which was specifically manufactured allowing for quick and easy changes for the different seating configurations (Figure 4 13). The experimental throwing frame was passed by a British Athletics Level 3 official as being suitable for national and international competitions and complied with World Para Athletics rules (World Para Athletics 2020 - 2021).

Figure 4 13: Experimental throwing frame.

b) Tridimensional kinematic data

Firstly, the order of participants and seating configuration was randomised. The data collection protocol was similar to Study 1B except there were more participants and so the process was repeated, including the following steps, as shown in Figure 4 14.

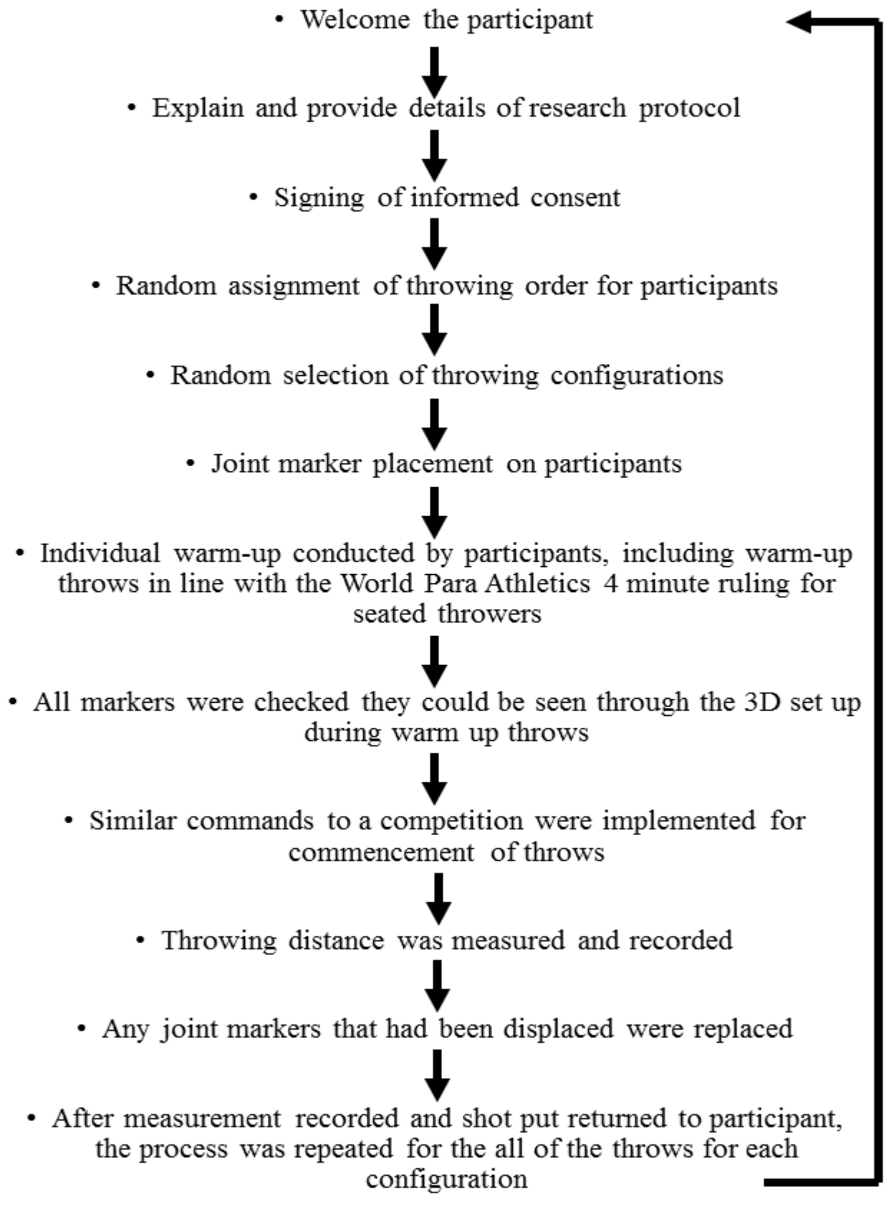


Figure 4 14: Flowchart for data collection protocol.

Participants wore a set of 81 reflective spherical markers, as previously described in Chapter 3. A seated static reference trial was recorded to determine the segmental coordinate systems, joint axes and anatomical positions. For the reference trial, markers were placed on the joints and parts of the throwing frame as well as the shot-put, as listed in Table 4 1.

As the point of release was the focus, a basic static model was created for visual representation only, as shown in Figure 4 15. Key upper body segments were identified and included trunk, elbow, shoulder and the hand. Details of how the upper body segments were generated are presented in Table C 1.

Figure 4 15: Visual representation of the 3D static model created in Visual 3D.

Three-dimensional kinematics data were collected at 250 Hz using an 20-camera Qualisys motion analysis system (Oqus 300/310, Qualisys AB, Gothenburg, Sweden) equally spaced around the throwing frame (Figure 4 2), which was a recommendation from Study 1A. Calibration was completed prior to data acquisition following the standard procedure recommended by Qualisys, as described previously. Calibration was accepted if average 3D residuals were estimated to be ≤1.0 mm.

Processing

The whole throwing movement was captured until a few instants after the release of the shot-put. The point of release and a flight trajectory including up to 10 frames post release, were identified during data capture as events and labelled as release and F_1 to F_10 respectively. The performance of each throw corresponding to the dependent variable was measured manually.

a) Conditions

Four seating Configurations A, B, C and D were considered, as previously described in Figure 4 8. These were chosen as they were initially identified as the most popular seating configurations currently used by world class seated shot-putters.

b) Datasets

For all the throwing trials, two separate datasets were considered in the analysis, which included:

- F_1 - the shot-put at the point of release (the last frame that the shot-put was in contact with the hand) was the focus alongside the flight trajectory identified by one point only, which was the first frame after the shot-put had left the hand (Figure 4 16 and Table 4 18) and was referred to as F_1, whereby Δ1 = 0.002 s,
- F_10 - the shot-put at the point of release was the focus alongside an extended flight trajectory to include a further nine points (Figure 4 17 and Table 4 18), i.e. F_2 to F_10, whereby Δ10 = 0.182 s.

Table 4 18: Critical frame location definitions.

Point of release	Last frame that the shot-put was in contact with the hand
F_1	First frame after the shot-put has left the hand
F_2 – F_10	Subsequent frames that show the movement of the shot-put
Δ1 flight trajectory	From point of release to the F_1 (t = 0.002s)
Δ10 flight trajectory	From point of release to the F_10 (t = 0.182s)

F_1 and F_10 flight trajectories were added as sets of events in Qualisys. The data was exported into Visual 3D as two separate data sets. The shot-put was tracked, alongside the joints of the body throughout the whole throwing movement, as described previously. All marker trajectories once exported into Visual 3D were filtered using a 3rd order Butterworth bi-directional low-pass filter with a cut-off frequency of 8 Hz, as described by Winter, Sidwell and Hobson (1973).

Figure 4 16: Point of release and 1st frame after (F_1).

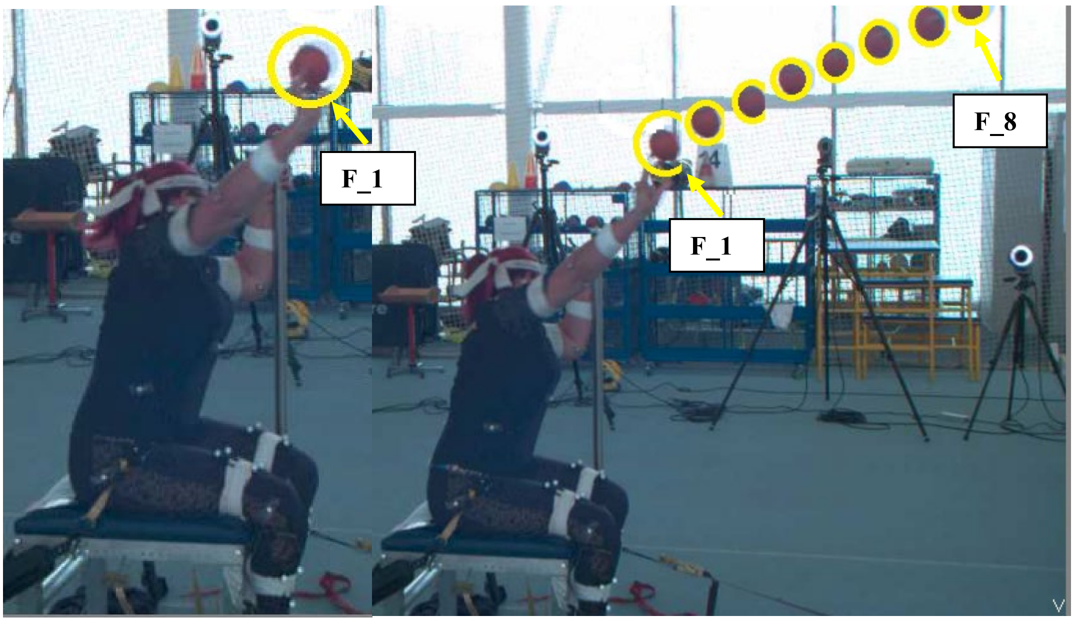


Figure 4 17: Flight sequence showing the point of release, F_1 – F_8 (F_9 and F_10 out of view).

c) Variables

The primary variable was the three-dimensional trajectory of the shot-put over time as determined by the reflective marker placed on the shot-put.

The secondary variables included:

- The dependent variable corresponding to the measured performance, expressed in metres, determined manually and corresponded to the nearest point of the shot-put landing to the point of measurement at the front of the throwing circle.
- The independent variables corresponding to the calculated performances based on:
  - The F_1 flight trajectory, in metres, corresponding to 1 frame after the release point, where t = 0.002 s
  - The F_10 flight trajectory, in metres, corresponding to 10 frames after the release point, where t = 0.182 s.

It should be noted that medial lateral data was exported but on observation it was decided to eliminate from further analysis due to the very low values recorded. This was also a reason why the equation for calculating shot-put flight trajectory detailed earlier was utilised as it involved horizontal and vertical velocity components at release (Linthorne 2001, Young 2001).

Horizontal displacement of the shot-put i.e. the performance was calculated within an excel spreadsheet. This allowed for flight distance to be determined for the two calculated performance variables. The calculation was generated by using the horizontal and vertical release velocities, the release height, the release angle and the release gain (the horizontal displacement between the front of the throwing circle and the release point). All these variables, apart from the release angle, were generated through metric commands created in Visual 3D, which are the discrete position and velocity values at a specific frame, such as the point of release. The release angle was calculated using Pythagorus' theorem from the horizontal and vertical components. The radius of the shot-put (0.06 m for 4 kg and 0.05 m for 3 kg) was then deducted from the calculated performance as the calculation is based on the centre of the shot-put. This is in contrast with the measured performance (the manual measuring of the distance thrown by an official) which is taken from the nearest landing point of the shot-put to the thrower i.e. the radius distance from the centre of the shot-put.

Comparison between measured and calculated performance

With regards to the difference between measured and calculated performance values, expressed in meters, the calculation error provides feedback on the quality of the data processing (Frossard, Smeathers, Evans, O'Riordan and Goodman 2008). The calculated performance for F_1 and F_10 flight trajectories were compared against the measured performance, with the latter taken as the reference value. In principle, after release, it can be assumed that the vertical velocity of the shot-put must be constant, with its acceleration equal to 9.81 ms^{-2}, whereas the horizontal velocity of the shot-put must be constant, and its acceleration nil.

Statistics

The calculated performance was compared to the measured performance using error analysis and to determine the percentage error for the F_1 and F_10 flight trajectories. The statistical analyses focused on included descriptive statistics, variability and error analyses.

a) Descriptive statistics

Basic descriptive statistics for the measured performance and the difference between measured and calculated performances were generated for the F_1 and F_10 flight trajectories across the four seating configurations. This included mean, standard deviation, maximum, minimum and the range, as explained in Table 4 19. All measured and calculated performances are presented in O'Riordan and Frossard 2020b.

Table 4 19: Definition and excel function utilised for the descriptive statistics.

Descriptive Statistic	Definition	Excel function
Mean	Average of all values	=AVERAGE
Standard deviation (SD)	The degree of variation from the means of the values, and is usually the best measure of spread (Hopkins 1977)	=STDEVA
Maximum (MAX)	The maximum value of all the values	=MAX
Minimum (MIN)	The minimum value of all the values	=MIN
Range	The difference between the maximum and minimum values	=(MAX-MIN)

b) Error analysis

The error (the difference between measured and calculated) was determined alongside absolute error, the mean square error (MSE), the root mean square error (RMSE), and the mean absolute percentage error (MAPE), as defined in Table 4 20 below.

Table 4 20: Error related definitions and equations.

Error	$\text{measured performance} - \text{calculated performance}$
Absolute error	Error expressed as an absolute value

MSE	$\frac{\sum_{F\_1 or F\_10}^{n} (Abs\ Error)^2}{n}$
RMSE	$\sqrt{MSE}$ or $\sqrt{\frac{\sum_{F\_1 or F\_10}^{n} (Abs\ Error)^2}{n}}$
MAPE	$\frac{\frac{\sum_{F\_1 or F\_10}^{n} (Abs\ Error)}{Measured\ Error}}{n} \times 100$

A scatterplot diagram was produced to consider differences in correlations of calculated to measured performance for the two flight trajectories (F_1 and F_10), as shown in Figure 4 18. Further scatterplot diagrams were constructed to consider differences in correlations between release velocity (horizontal and vertical) against measured performance for the two flight trajectories (F_1 and F_10), as shown in Figure 4 19.

4.3.2 Results

As presented in Table 4 21, the mean measured performance of the F_1 flight trajectory was shorter than the F_10 flight trajectory across all seating configurations. The differences in the mean values between the measured performance and F_1 and F_10 flight trajectories respectively, were 61% and 98% for Configuration A, 59% and 93% for Configuration B, 65% and 92% for Configuration C and 65% and 99% for Configuration D.

Table 4 21: Descriptive statistics of the measured and calculated performances for F_1 and F_10 flight trajectories, expressed in metres, for seating Configurations A, B, C and D. (SD: standard deviation, Max: maximum value, Min: minimum value, n = no of throws).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
Measured Performance	n = 36	n = 36	n = 36	n = 36
Mean	7.30	7.13	7.05	6.68
SD	1.79	1.38	0.85	0.92
Max	9.65	9.52	8.76	8.30
Min	3.13	3.82	5.25	5.29
Range	5.52	5.70	3.51	3.01
Ranking	1	2	3	3
Calculated Performance F_1 flight trajectory	n = 33	n = 33	n = 33	n =33
Mean	3.53	3.20	3.62	3.31
SD	1.73	1.37	1.66	1.39
Max	7.50	6.63	7.63	6.83

Min	1.99	1.66	1.72	1.78
Range	5.51	3.98	5.90	5.05
Ranking	2	3	1	3
F_10 flight trajectory	n = 33	n = 33	n = 33	n = 33
Mean	7.03	6.69	6.38	6.75
SD	1.51	1.39	1.31	1.65
Max	9.66	9.76	9.97	11.85
Min	3.75	3.66	3.39	3.06
Range	5.90	6.10	5.57	7.79
Ranking	1	3	4	2

In all instances, calculated performances increased from F_1 to F_10 flight trajectories. The latter trajectory was closer to the measured performance as shown by the regression lines, with correlations much greater for Configurations A and B than C and D (Figure 4 18).

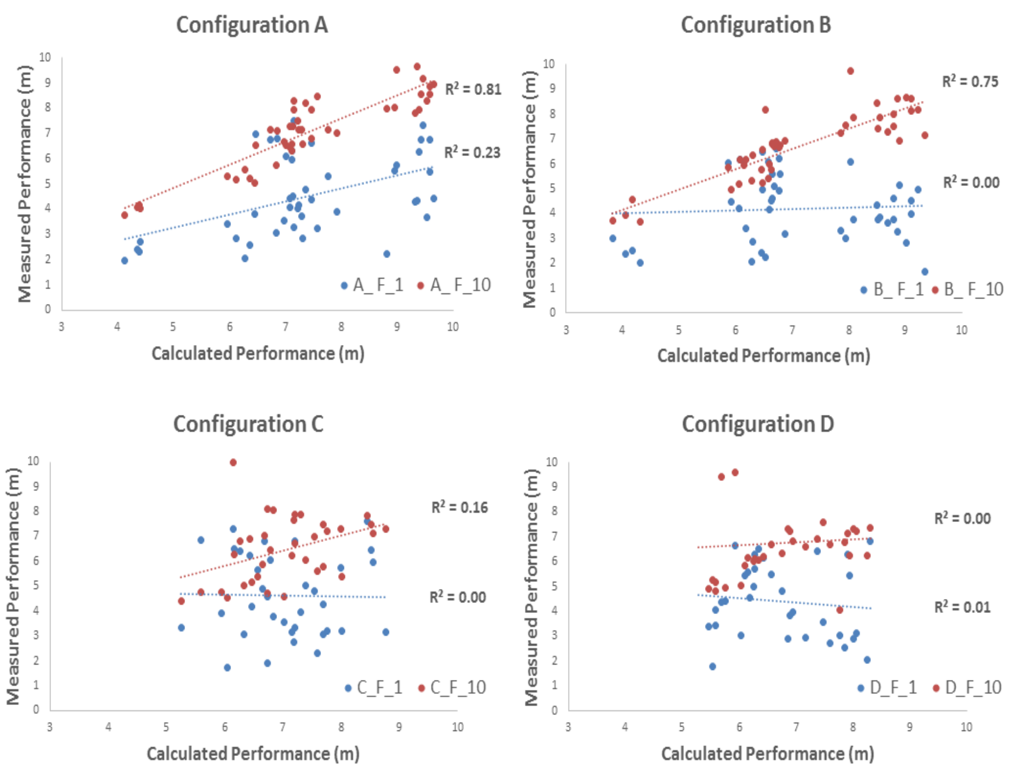


Figure 4 18: Scatterplot diagrams of measured against calculated performance for F_1 and F_10 trajectories (n = 36 for Measured Performance and n = 33 for Calculated Performance) for Configurations A, B, C and D, respectively).

Additionally, the release velocities also increased from F_1 to F_10 flight trajectories for all seating configurations, as shown in Figure 4 19.

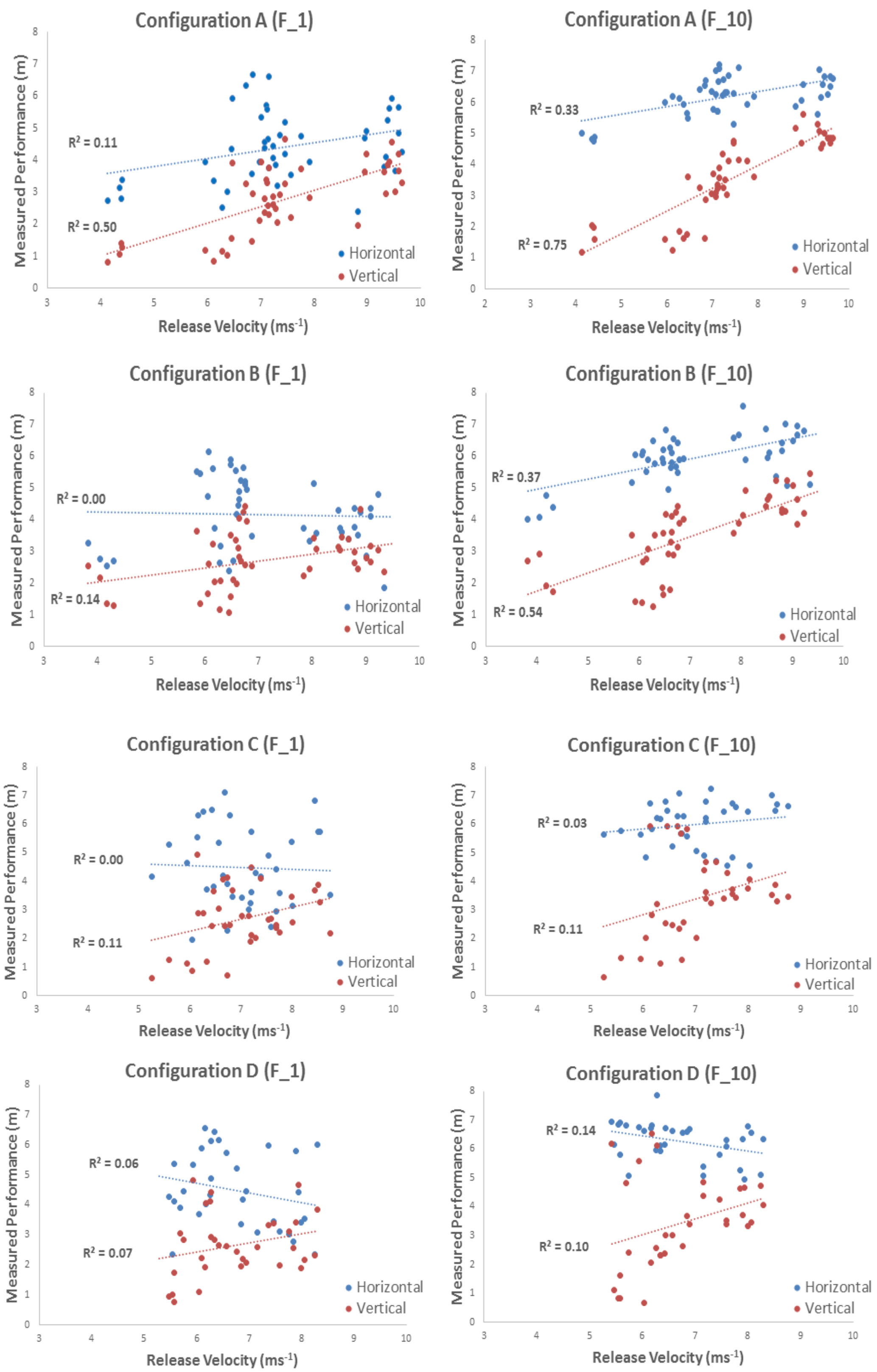


Figure 4 19: Scatterplot diagmrams of release velocity against measured performance for F_1 and F_10 trajectories (n = 36 for Configurations A, B, C and D, respectively).

Descriptive statistics for the error difference between measured and calculated performance across the four seating configurations were generated and are presented in Table 4 22. The mean of the error ranged from 2.36 m to 2.90 m for the F_1 flight and -0.03 m to 0.60 m for the F_10 flight, with the standard deviation much reduced for the F_10 flight also.

Table 4 22: Descriptive statistics for the error (difference between measured and calculated performance), across the four seating Configurations for F_1 and F_10 flight trajectories.

Seating Configuration	**A**		**B**		**C**		**D**	
	F_1	F_10	F_1	F_10	F_1	F_10	F_1	F_10
No of trials	33		33		33		33	
Mean (m)	2.87	0.37	2.90	0.30	2.39	0.60	2.36	-0.03
SD (m)	1.59	0.67	1.95	0.73	1.88	1.25	1.82	1.80
Max (m)	6.59	1.50	7.68	2.17	5.58	2.63	6.20	3.10
Min (m)	0.50	1.16	0.18	1.73	-1.29	-3.83	-0.72	-5.57
Range (m)	6.09	2.65	7.86	3.90	6.87	6.35	6.92	8.67

MSE error values ranged from 8.77 m to 12.12 m for the F_1 flight and 0.57 m to 3.13 m for the F_10 flight, whilst RMSE error values ranged from 2.96 m to 3.38 m for the F_1 flight and 0.76 m to 1.77 m for the F_10 flight. MAPE error values ranged from 33.31 to 39.26% for the F_1 flight and from 8.87 to 17.55% for the F_10 flight, as shown in Table 4 23.

Table 4 23: Error related statistics across the four seating Configurations for F_1 and F_10 releases, where MSE is the mean square error, RMSE is the square root of the mean square error and MAPE is the mean absolute percentage error.

Seating Configuration	**A**		**B**		**C**		**D**	
	F_1	F_10	F_1	F_10	F_1	F_10	F_1	F_10
MSE (m)	10.73	0.57	12.12	0.70	9.62	1.88	8.77	3.13
RMSE (m)	3.28	0.76	3.38	0.83	3.10	1.37	2.96	1.77
MAPE (%)	39.26	8.87	39.00	8.27	37.23	16.29	33.31	17.55

4.3.3 Discussion

The purpose of this study was to consider and determine the error that might be present when focusing on the release parameters of seated shot-putters. Of particular interest was how different flight trajectories might influence the release parameters. The error was assessed by comparing measured to calculated performance for two flight trajectories, including t = 0.002 s which was one frame post release and t = 0.182 s which was 10 frames post release.

Across all the seating configurations, the mean calculated performance for the F_10 trajectory was higher than for the F_1 trajectory, with the former being 37%, 35%, 27% and 33% higher for Configurations A, B, C and D respectively. This is likely due to the visible increase in vertical and horizontal release velocities from F_1 to F_10 trajectories, as shown in Figure 4 19.

The mean of the calculated performances (F_1 and F_10) were shorter than the measured performance for all seating configurations apart from Configuration D. This might suggest that this configuration is one that produces more inconsistency in performance.

Improvements in the RMSE and MAPE values were evident between the F_1 and F_10 conditions, with the longer flight trajectory (F_10) having the least error. Although much less for the F_10 condition the largest MAPE value was still less than 18%, and was considered satisfactory based on sample size and conditions. Error also increased from seating Configurations A to B to C to D, with A and B showing much less error than C and D, for both F_1 and F_10 conditions. The reason for this will be investigated in Study 2 where configuration efficacy with regards to performance will be considered.

It is important to remember that the calculated distance is being considered using only the horizontal and vertical velocities, as explained in the introduction, assuming the situation is a two-dimensional one. However, the motion occurs in the three planes of the GCS. Thus, the medial-lateral velocity will also affect the resultant velocity. This then directs attention to the possibility of the athlete throwing out of the 2D plane and how different angles can affect overall calculated horizontal distance (performance). Another possible source of error might be the placement of the calibration frame between testing of participants. Although the placement was consistent across all the seating configurations any differences would show in the error values, albeit consistently. Additionally, although best effort was made to avoid this by marking where the legs of the throwing frame should be, if there had been any movement of the throwing frame during the entire testing procedure this would also impact on this alignment and subsequent error.

This concept of being out of plane is important when considering the error across the seating configurations with error increasing from A to B to C to D, with C and D having significantly greater error. The former two seating Configurations (A and B) employed the use of the holding pole which may have influenced the throwing movement by providing a “corridor” through which the movement could occur thus limiting medial-lateral movement, especially on release. This may be even more important in athletes with trunk limitations affecting balance and stability, whereby the holding pole is used to assist with these key functional throwing movements.

A comparative analysis between measured and calculated performance is useful for providing feedback on the quality of data processing and generating recommended protocols for subsequent data processing and analysis. However, the relevant error sources need to be acknowledged and considered.

Limitations specific to Study 1C

There were possible errors sources associated with the static nature of the measurement equipment, protocols employed, and with using theoretical equations to calculate performance within Study 1C. Additionally, errors associated with the measured performances should be considered.

The inter-rater variability was likely to be high. It was reliant on the experience and accuracy of the official being able to reliably sight the landing of the shot-put on a hard surface (as it was an indoor facility), and keeping the landing point in sight whilst moving to make the measurement.

Measurement was made by pulling a flexible measurement tape from the point of landing through the centre of the throwing circle. In accordance with the rules of the sport, the measurement was taken at the near edge of the stop board at the front of the throwing circle (World Athletics 2019 and WPA 2020 - 2021). There would also be error associated with the measurement device which is made of a flexible material, and the angle that it is pulled through towards the centre of the circle.

Athletics, as a sport, has tried to minimise such error, especially in the long throws, by now employing Electronic Distance Measurer (EDM) systems. Although the correct sighting of the shot-put landing will still be a possible error the actual measurement should be more accurate as it is done automatically through calibration at the start of the event.

4.3.4 Conclusion

From this study, it is evident that there is much less error for the F_10 flight condition. It was clear that a larger Δt produces greater accuracy of the release parameters so this will be the protocol used for the processing and analysis formulating the following main studies.

This error analysis identified important considerations to the 3D analysis of release parameters and could be applied to any throwing, hitting or striking sports involving flight, particularly if they involve tri-dimensional trajectories and two-dimensional measurements. The considerations include:

- the importance of implementing a quality control procedure within kinematic analysis
- the need to be precise in defining and ascertaining key instances such as the point of release and the length of the flight trajectory
- the importance of reporting outcomes considering both error and calculated quality.

Chapter 5: Study 2

Seating configuration, shot-put release variables and performance in elite seated shot-putters.

Some outcomes of this chapter are presented in the following publications:

- O’Riordan A and Frossard L (2020a) - Coaching Seated Shot-put: New Perspectives, Australian Track and Field Coaches Association Coaching Journal, Winter 2020.
- O’Riordan A and Frossard L (2020c) - Inter-participant variability data in performance of elite seated shot-putters throwing from different seating configurations, *Mendeley Data, VI*, doi:10.17632/wbj6vyy6z6.l.

The content of this chapter will be presented in the following publications:

- O’Riordan A and Frossard L – Can a seating configuration affect performance of seated shot-putters? To be submitted to Scandinavian Journal of Medicine and Science in Sports, April 2021
- O’Riordan A and Frossard L – How seating positions change seated shot-put release variables. To be submitted to Journal of Science and Medicine in Sport, May 2021.
- O’Riordan A and Frossard L – Shot-put performance: what is the best of the best? To be submitted to Exercise and Sport Sciences Reviews, June 2021.

Abstract

Aim: To identify which of four seating configurations (A, B, C or D), had the most favourable influence on performance of elite seated shot-putters. This was done by exploring the shot-put release variables and how they impact performance. ***Methods***: The same eight elite level Class F55 and F56 participants from Study 1C were used. A total of 40 variables were considered, including the release parameters of vertical, horizontal and resultant velocity, angle, height and gain for all and best throws datasets, from the same four seating configurations utilised in Study 1 (B and C). Pearson's correlation analysis was conducted to determine the relationship of the release variables against performance. The deterministic model of Tier 1 (the release) was populated with the r correlation values for each seating configuration. The concept of efficacy was created and defined as the capacity to impact performance where an efficient seating configuration will increase performance. ***Results***: Seating Configuration A showed strongest efficacy alongside the greatest number and stronger correlations to performance for the release variables. Vertical release velocity and release height showed the strongest correlations. This was followed by seating Configurations B, D and C ranked by order of efficacy. ***Conclusion***: The seating configurations that used a holding pole (A and B) showed similar results with regards efficacy together with the higher number and greater strength of correlations of release variables to performance. Clearly, holding a pole was the most beneficial to improve performance.

5.1 Introduction

Presently, throwing frame configuration, referred to as seating configuration in this study, and specific throwing technique for seated shot-putters is largely based on a trial-and-error approach (Frossard O'Riordan and Goodman 2010). Seating configuration relates to both sitting direction and whether a holding pole is used or not. There are currently a variety of seating configurations utilised by seated shot-putters, including sitting in front on or diagonal on directions, with or without the use of a holding pole. This is evident when watching footage from major competitions such as Paralympic Games. There is currently limited evidence identifying which seating configuration might be more beneficial to promote performance.

Impact of research outcomes has been described as the product of the efficacy of the research and the implementation into the real-life sport setting (Bishop 2008). Thus, efficacy in this study relates to the seating configuration that has the capacity to positively impact performance.

Throwing theory regarding the characteristics that influence projectile flight and the flight characteristics of shot-put were introduced in Study 1C. Relevant information on the release characteristics and the relationship between them follow below.

Release Characteristics

There is a substantial amount of research of the release characteristics for standing shot-putters (McCoy, Gregor, Whiting, Rich and Ward 1984; Tsirakos, Bartlett and Kollias 1995; Ariel, Probe, Penny, Buijs, Simonsen and Finch. 2005). Release velocities from finalists at World Championships have been for male and females respectively, 13.28 ±0.22 and 13.83 ±0.24 (Mendoza, Nixdorf, Isele and Gunther 2009), 13.25 ±0.38 and 13.13 ±0.31 (Oh, Shin, Choi, Jeong, Bae, Lee and Oark 2011) and 13.69 ±0.26 and 12.74 ±0.37 ms^{-1} (Dinsdale, Thomas, Bissa and Merlino 2017). Release heights for elite level athletes are typically between 2 and 2.2 m (McCoy Gregor, Whiting, Rich and Ward 1984; Tsirakos, Bartlett and Kollias 1995; Alexander, Lindner and Whalen 1996; Mendoza, Nixdorf, Isele and Gunther 2009; Dinsdale, Thomas, Bissa and Merlino 2017; Oh, Shin, Choi, Jeong, Bae, Lee and Oark 2011).

As for release angle, the large majority of both elite and sub-elite level standing performers release the implement at an angle considerably lower than 40 degrees from the horizontal

(McCoy 1992b; Maheras, 1995; Luhtanen, Blomquist and Vanttinen 1997; Ariel, Probe, Penny, Buijs, Simonsen and Finch 2005; Mendoza, Nixdorf, Isele and Gunther 2009; Oh, Shin, Choi, Jeong, Bae, Lee and Oark 2011; Dinsdale, Thomas, Bissa and Merlino 2017). Some have seen release angles greater than 40 degrees (Stepanek 1987; Tsirakos, Bartlett and Kollias 1995; Ariel, Probe, Penny, Buijs, Simonsen and Finch 2005).

The initial limited research conducted for seated shot-putters focused predominantly on the parameters of the throwing implement's trajectory and on upper body kinematics (Chow and Mindock 1999; Chow, Chae and Crawford 2000; Chow, Kuenster and Young-tae 2003; Frossard, Smeathers, O'Riordan and Goodman 2007). Results highlighted lower release variables for seated athletes compared to standing athletes. For example, speed of release for seated athletes was 5.3 – 7.8 ms^{-1} (with increasing function) compared to 13.2 ms^{-1} (McCoy Gregor, Whiting, Rich and Ward 1984), 11.4 (Dessureault 1977) and 10.6 ms^{-1} (Alexander, Lindner and Whalen 1996). Similarly angles of release were less for the seated athletes, 19.8 – 33.7 degs (with increased function) compared to 37.2 degs (Alexander, Lindner and Whalen 1996), 36.8 degs (Dessureault 1977), 36.3 degs (McCoy Gregor, Whiting, Rich and Ward 1984) and 36.55 to 36.67 degs (Dinsdale, Thomas, Bissa and Merlino 2017a and 2017b).

Relationships between Release Characteristics

Release velocity and angle of release have been shown to have an inverse relationship i.e. an increase in release angle will see a decrease in release velocity (Maheras 1995; Hubbard, de Mestre and Scott 2001), Release velocity is considered to be the most important of all the release variables as horizontal displacement of the shot-put is proportional to the release velocity squared (Young and Li 2005).

Release angle is influenced by the angle of extension of the throwing arm in relation to the angle of the athlete's trunk in the sagittal plane. This maybe of significance in seated shot-putters with compromised trunk function and unable to either maintain an upright posture and/or create forward lean on release without external support, such as a holding pole. It is the careful manipulation of the release angle without negatively impacting on the release velocity that athletes are trying to optimise.

It would be anticipated that height of release would generally stay consistent as will largely depend on the shot-putter's anthropometry (i.e. height and length of throwing arm) being the main determinant. For seated shot-putters this relates to trunk and throwing arm length plus the height of the throwing frame from the ground (75 cm). As release height can influence performance an athlete with long arms and stable trunk should be better suited for the seated shot-put event.

Release characteristics focus on the movements of the shot-put at the moment of release. They do not provide any information on the participants' movements prior to release. Efficient shot-put technique is characterised by movement of the shot-put through a large range of motion and involves minimal slowing of the shot-put in the preparatory movements. This should be followed by maintenance of a favourable throwing position at the end of these movements, particularly into and out of the power position, and correct sequencing of the body motions during the delivery (Dyson 1986; Hay 1993).

Rules regarding seating position and throwing frame design have changed since the research conducted by Chow, Chae and Crawford (2000), with athletes now subjected to more task-led constraints. One such constraint is having to remain seated throughout the whole throwing movement. This thesis focuses on release variables of seated shot-putters and is the first of its kind to be conducted since the new rules were implemented in 2014.

Two aggregated data sets were considered here, one including all throws and the other, the best of the throws, per participant for each seating configuration. Generally, there are two schools of thought around the analysis of data in sports related research, i.e. observational studies versus performance related analysis (Hopkins 2000; Bishop 2008; O'Donoghue 2010). The former typically relies on the mean and standard deviation of variables to compare cohorts of participants (e.g. asymptomatic vs symptomatic) and is often referred to as a descriptive approach. Consequently, we considered the performance of all throws performed by the participants represented by a mean and standard deviation.

However, this approach might only be partially relevant in the field of sport science, especially when focusing on performance differences between elite athletes. Alternatively, a more performance-based analysis was included by aggregating only the best throws.

This latter approach is likely to be more relevant in this present study since the longest throwing distance achieved of the six attempts during a competition is the one that is used to ascertain placings and medals at global games, thus making it much more applicable for athletes and coaches. The downside of best throws is the limited number of samples that can be considered and therefore it limits the statistical analyses. This best-throws dataset was only used for the descriptive and correlation analyses.

The importance of best throws on competition outcomes can be seen when looking at results from the most recent global para athletics championships, the 2019 WPA World Championships. In the F55 male shot-put event, the gold, silver and bronze medals were won with distances of 12.25 m, 12.10 m and 12.01m respectively, based on the longest throw of the six available per athlete. However, if the mean of the six throws was to be considered the final result would be very different, with the gold medallist moving to the bronze medal position with a mean performance of 11.97 m, with the 2nd and 3rd placed athletes who demonstrated more consistent performances across their six throws with a lower difference between their mean and best performances.

This impact of best throws on competition results was further highlighted in the F57 female shot-put event where the bronze medallist recorded only one throw of the six on offer, which was enough to secure the medal. There were two athletes in lower placings that recorded much higher mean performances and thus were technically more consistent. Coaches do work with athletes to improve consistency of throwing, but as can be seen with the examples above, it is the best (longest) throw that secure the result.

Differences in best and mean performances also featured in an e-book of all seated throws results from the 2005 IPC Athletics World Championships (Frossard, O'Riordan and Goodman 2009). However, at that time there were no outcome differences between the best and mean throws for the medal winning performers. A reason for this might be that the depth of competitive athletes at that time was less than it is now. As mentioned previously, the rules regarding frame design and throwing technique were different in 2005 (Table 2 2) and so the outcomes from this earlier research are only partly applicable to today's situation.

A inter throw (throw to throw) coefficient of variance analysis was conducted to ascertain variability between performance and the shot-put variables at release (Tier 1). Tier 1 is the point of release and is the focus for this study. If low variability was shown across the release variables, it would then be appropriate to conduct an intra participant coefficient of variance analysis. High inter throw variability would be expected for a symptomatic population.

A deterministic model for seated shot-put based on the outcomes of a thorough review of seated throwing literature was developed (Figure 3 5) with the intention that it would be populated with correlation coefficient values from the data analysis undertaken from this study. By presenting the data in visual form, it was hoped the outcomes would become more accessible and user friendly to coaches and athletes.

Aim, purposes and objectives

The ultimate goal of this study was to provide guidelines for coaches and athletes to enable better evidenced-based decision making when choosing a seating configuration to improve performance. This would be done in this study by exploring the shot-put release variables and how they impact on performance.

Aim

The aim of this study was to identify which of four seating Configurations A, B, C or D, had the most favourable impact on performance of elite seated shot-putters.

Purposes

The purposes to this study were to:

- Determine the magnitudes of shot-put release variables for each seating configuration
- Apply correlation coefficient values to the deterministic model of seated shot-put.

Objectives

The specific objectives were to:

- Present and compare the throwing performances of all throws and the best throws for seating Configurations A, B, C and D.
- Establish the relationship between seating Configurations A, B, C and D, shot-put release variables and performance.
- Report how the variability of the shot-put release variables and performance is affected by seating configurations with an emphasis on inter and intra-participant variability.

5.2 Methods

Essential methodological aspects of data capture and processing used in this study has been detailed in Chapter 4. Therefore, only necessary information will be presented here.

Participants

The same participants were used as in Study 1C which included eight elite level seated shot-putters from classifications F55 (n = 3) and F56 (n = 5), which represented 23% of the total population of elite athletes in these classes worldwide (37 ±10 years, 1.79 ±0.18 m, 95.33 ±26.02 kg).

Apparatus

The same experimental throwing frame and 20 tridimensional camera arrangement were used as in Study 1C (Figure 4 13). The data collection process detailed in Figure 4 14 was also followed.

Processing

A 3D kinematic model of the relevant joints, throwing frame and shot-put was created in Qualisys. The point of release was manually identified as the last frame that the shot-put was in contact with the hand and identified as an event. The raw 3D kinematic data were exported into Visual3D motion system (Version 4.21, C-Motion Inc., Germantown, Maryland, USA), which was used to further process the kinematic data. All markers' trajectories were filtered using a 4th order Butterworth bi-directional low-pass filter with a cut-off frequency of 8 Hz.

a) Conditions

The same seating Configurations (A, B, C and D) as seen in Studies 1B and 1C were utilised for this study, as shown in Figure 4 8.

b) Datasets

Two separate datasets were considered in the analysis, which included:

- All throws - all the throwing trials per participant for all seating configurations
- Best throws – the longest throw per participant for each seating configuration, involving the release variables associated with each of the longest throws.

c) Variables

The primary variable was the three-dimensional trajectory of the shot-put over time as determined by the reflective marker placed on the shot-put.

The secondary variables included:

- The dependent variable corresponding to the performance measured from the front of the throwing circle to the nearest landing point of the shot-put.
- The independent variables corresponding to the shot-put release variables including:

- Vertical velocity
- Horizontal velocity
- Resultant velocity
- Angle
- Height
- Gain: release distance ahead or behind of front of shot-put circle where the performance measurement is taken.

The shot-put release velocities, height and gain were determined through Visual 3D pipeline metrics. All data were exported into excel for analysis. It should be noted that the release height was determined as the height within the global coordinate system, which was situated on the top of the throwing frame seating area. Consequently, the 75 cm height of the throwing frame was added to this exported height value giving the overall release height.

Resultant release velocity and angle were determined using Pythagoras theorem calculated in excel with the following functions;

- Resultant release velocity: =SQRT(Horizontal release velocity^2+vertical release velocity^2)
- Release angle: =DEGREES(ATAN(Horizontal release velocity/vertical release velocity)).

Statistics

This thesis is exploring an area that has had minimal research conducted particularly from a performance improvement perspective. Consequently, it was decided to use a research question rather than a hypothesis, as explained in Chapter 1. Nonetheless, the statistical analyses focused on descriptive statistics, variability analysis, correlation analysis, linear regression analysis and ANOVA, with the latter three undertaken using IBM SPSS Statistics, version 25.

a) Descriptive statistics

Datasets were presented using basic descriptive statistics including mean, standard deviation, maximum, minimum and the range as detailed in Table 5 1.

Table 5 1: Definition and excel function utilised for the descriptive statistics.

Descriptive Statistic	Definition	Excel function
Mean	Average of all values	=AVERAGE
Standard deviation (SD)	The degree of variation from the means of the values, and is usually the best measure of spread (Hopkins 1977)	=STDEVA
Maximum (MAX)	The maximum value of all the values	=MAX
Minimum (MIN)	The minimum value of all the values	=MIN
Range	The difference between the maximum and minimum values	=(MAX-MIN)

b) Variability

The variability of the secondary variables was explored by using the coefficient of variation (COV) corresponding to the standard deviation divided by the mean (Chattopadhyaya and Kelley 2016). COV is a measure of a standardized effect size expressing the degree of variability with respect to central tendency also sometimes expressed as a percentage of the mean for both intra and inter participant variation. A within (intra) participant coefficient of variation analysis is regarded as an important measure of reliability and can be of interest to coaches wanting insight of athlete performances between competitions (Hopkins 2007). Having a low variability might be linked to efficacy of the design and can be applied to this research when focusing on seated thrower's performances within a series of six throws for each seating configuration.

There is some discussion in the academic community around variability thresholds with little actual evidence defining these thresholds and appear to be dependent on the field of study. Here, we considered that a COV less or more than one represented a low or high variability, respectively. Inter (throw-to-throw) and intra (participant-to-participant) trial COV were calculated to assess variability between all participants and throwing trials (O'Riordan and Frossard 2021c).

c) Individual contribution of secondary variables to performance

Correlation is an association between two variables and is used to assess a possible linear relationship between these variables (Munaka 2012). The correlation coefficient, known as r, is the measure of the relationship strength (Field 2009). Correlations can be positive or negative with the two variables being proportional to each other for a positive relationship.

As a method of initial data assessment, scatterplot graphs were constructed to show the relationship of the performance against the shot-put release variables (Figure D 2– Figure D 6) for all participants and all throwing trials.

A Pearson's correlation analysis followed to determine the r value, significance and strength of association described using the ranges set by Hopkins (2002) which was developed from the initial work of Cohen (1988), and is represented in Table 5 2 below. A positive correlation coefficient means that when the value of one variable increases the value of the other variable increases too. This is in contrast to a negative correlation coefficient whereby, if the one variable increases, the other decreases.

Table 5 2: Interpretation of size of correlation coefficients (adapted from Hopkins 2002).

Size of Correlation	Interpretation
0.90 - 1	Almost perfect
0.70 – 0.90	Very strong correlation (positive or negative)
0.50 – 0.70	Strong correlation (positive or negative)
0.30 – 0.50	Moderate correlation (positive or negative)
0.10 - 0.30	Low correlation (positive or negative)
0.0 – 0.10	Negligible correlation (positive or negative)

d) Relative contribution of secondary variable to performance - Stepwise linear regression

Stepwise regression analysis, including backward and forward, can be used to quantify the relationship between a number of independent variables to a dependent variable. However, how the variables to be included are selected is important to eliminate any bias (Steyerberg, Eijkemans and Habbema 1999). A stepwise (backward) linear regression analyses was conducted to ascertain which shot-put release variable might contribute the most to performance, for all throws.

In a backward regression, all variables are inputted in the beginning, and the analysis eliminates those with less significance, through a series of stages, leaving those variables with the most impact. Shot-put gain, as a release variable, was not included in analyses for all seating configurations, as it had been shown to have high variability in some instances, and negligible correlation.

The unstandardized coefficient (B) values in the output are the values for the regression equation that predict the dependent variable from the independent variable and are measured in their own units. As such the independent variables cannot be compared with each other as they all have their own unit scaling. Thus, for each one-unit increase, for a particular independent variable, will see the relative B value increment increase or decrease. However, it is important to present the information with increases/decreases that are realistic and meaningful in a seated shot-put coaching context e.g. a 1 m^{-1} increase in velocity will be presented as a $0.1ms^{-1}$ increase. The subsequent performance increase/decrease will then be divided by 10 to get the comparative figure.

e) Analysis of variance

A repeated measures two-way ANOVA is used to compare the mean differences between three or more samples that have been split into within-participants factors, referred to as independent variables (O'Donoghue 2010). It was used in this research to consider the effect of sitting direction and use of holding pole, the independent variables, and their interaction on the shot-put release variables for each seating configuration. It was only applied to the all throws dataset due to the low sample size for the best throws.

5.3 Results

Mostly descriptive results will be presented here. Other relevant results appear either in Appendix D or in O'Riordan and Frossard (2020c).

Overview

A total of 157 throws were analyzed including 44, 44, 35, and 34 throws in seating Configuration A, B, C and D, respectively, as detailed in Table 5 3.

Table 5 3: Grouped and individual number of throwing trials in each seating configuration.

Participant	**A** Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole	**Total**
1	6	5	6	6	23
2	5	6	6	5	22
3	6	6	6	6	24
4	6	6	6	6	24
5	5	5	6	6	22
6	6	6	5	5	22
7	6	6	0	0	12
8	4	4	0	0	8
Total	44	44	35	34	157

Performance

As presented in Table 5 4, the mean performance of all throws was lower than the mean performance of best throws across all seating configurations, where the differences in the mean values were 1% for Configuration A, 2% for Configuration B, 5% for Configuration C and 5% for Configuration D, respectively.

Table 5 4: Descriptive statistics of the performances expressed in metres for all throws and best throws for seating Configuration A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	7.40	7.13	7.05	5.58
SD	1.79	1.48	0.85	0.92
COV	0.24	0.21	0.12	0.14
Max	9.55	9.52	8.75	8.30
Min	4.13	3.82	5.25	5.29
Range	5.52	5.70	3.51	3.01
Ranking	1	2	3	4
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	7.50	7.28	7.45	7.04
SD	1.53	1.58	0.85	1.00
COV	0.22	0.23	0.11	0.14
Max	9.55	9.34	8.75	8.30
Min	4.41	4.31	5.59	5.04
Range	5.24	5.03	2.07	2.25
Ranking	1	3	2	4

The coefficient of variation ranged between 0.12 m and 0.21 m for the mean of all throws, and between 0.11 m and 0.23 m for the mean of the best throws. There was low intra variability (throw to throw) across all seating configurations for all throws and the best throws, with A and B recording slightly higher variability than C and D (O'Riordan and Frossard 2020c). The coefficient of variation ranged between 0.12 m and 0.21 m for the mean of all throws and between 0.11 m and 0.23 m for the mean of the best throws.

As presented in Table D 9, there were main effects ($p = \leq 0.05$) on performance of sitting direction ($F = 8.05$, $p = 0.04$) and use of holding pole ($F = 7.05$, $p = \leq 0.05$). This suggests that:

- the front on sitting direction produces greater performance than the diagonal sitting direction, regardless of whether a holding pole was used

- using a holding pole produces greater performance regardless of sitting direction.

Shot-put Vertical Velocity

As presented in Table 5 5, the differences between the means of all throws and the best throws for shot-put vertical velocity were 5% for seating Configuration A, and 1% for Configurations B, C and D, respectively. There was low intra throw variability across all seating configurations for means of all throws and best throws, with C and D recording slightly higher variability than A and B (O'Riordan and Frossard 2020c).

Table 5 5: Descriptive statistics of the vertical velocities of the shot-put expressed in ms^{-1} for all throws and best throws for seating Configuration A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	3.54	3.53	3.41	3.43
SD	1.25	1.14	1.43	1.55
COV	0.35	0.32	0.42	0.45
Max	5.53	5.45	5.93	5.52
Min	1.18	1.27	0.55	0.57
Range	4.45	4.18	5.28	5.85
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	3.34	3.51	3.38	3.39
SD	1.24	1.34	1.55	1.88
COV	0.37	0.38	0.45	0.55
Max	4.85	5.45	5.83	5.11
Min	1.50	1.74	1.27	0.57
Range	3.25	3.71	4.55	5.44

Relationship between shot-put vertical velocity and performance

The strength of the correlation between performance and shot-put vertical velocity is presented in Table D 2. Only correlations of >0.5 (strong or above) will be reported below:

- very strong for Configurations A and B, for all throws,
- very strong for Configurations A and B, for best throws.

As presented in Table D 8, shot-put vertical velocity was a significant ($p<0.01$) variable for seating Configurations A, C, and D, whereby a 0.1 ms^{-1} increase in shot-put vertical velocity would bring about a;

- 0.20 m increase in performance for seating Configuration A,

- 0.23 m decrease in performance for seating Configuration C,
- 0.22 m decrease in performance for seating Configuration D.

Shot-put vertical velocity had been eliminated from seating Configuration B through the stepwise regression process. There were no main effects ($p \leq 0.05$) of sitting direction and use of holding pole for shot-put vertical velocity, as presented in Table D 8.

Shot-put Horizontal Velocity

As presented in Table 5 6, the differences between the means of all throws and the best throws for shot-put horizontal velocity were 1% for seating Configuration A, 2% for Configuration B, 1% for Configuration C and 3% for Configuration D, respectively. There was similar low intra throw variability across all seating configurations for all throws and best throws (O'Riordan and Frossard 2020c).

Table 5 6: Horizontal velocities of the shot-put (in ms^{-1}) represented by the mean and standard deviation of all throws and best throws, for seating Configurations A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	5.20	5.95	5.00	5.27
SD	0.53	0.78	0.77	0.57
COV	0.10	0.17	0.13	0.11
Max	7.23	7.50	7.23	7.87
Min	4.75	4.01	4.55	4.95
Range	2.47	3.59	2.58	2.91
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	5.24	5.78	5.02	5.48
SD	0.55	0.88	0.93	0.89
COV	0.11	0.15	0.15	0.14
Max	5.87	7.03	7.07	7.87
Min	4.89	4.40	4.55	5.12
Range	1.98	2.50	2.52	2.75

Relationship between shot-put horizontal velocity and performance

The strength of the correlation between the performance and the shot-put horizontal velocity is presented in Table D 3. Only correlations of >0.5 (strong or above) will be reported below:

- strong for seating Configurations A and B, for all throws,

- very strong for seating Configuration A, strong for Configurations B and D (negative), for the best throws.

As presented in Table D 8, shot-put/hand horizontal velocity was a significant ($p<0.01$) variable for seating Configurations B, C and D, whereby a 0.1ms^{-1} increase in shot-put/hand horizontal velocity would bring about a;

- -0.22 m decrease in performance for seating Configuration B,
- 0.16 m increase in performance for seating Configuration C,
- 0.12 m increase in performance for seating Configuration D.

Shot-put horizontal velocity had been eliminated from seating Configuration A through the stepwise regression process.

There was a main effect of the interaction between sitting direction and use of holding pole ($F = 7.75$, $p = 0.04$) on shot-put horizontal velocity suggesting that using a holding pole from a front on sitting direction produces greater shot-put horizontal release velocity, as presented in Table D 9.

Shot-put Resultant Velocity

As presented in Table 5 7, the differences between the means of all throws and the best throws for shot-put resultant velocity were 1% for seating Configuration A, 2% for Configuration B, 1% for Configuration C and 3% for Configuration D, respectively. There was similar low intra throw variability across all seating configurations for all throws and best throws (O'Riordan and Frossard 2020c).

Table 5 7: Resultant velocities of the shot-put (in ms^{-1}) represented by the mean and standard deviation of all throws and best throws, for seating Configurations A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	7.21	5.99	7.02	7.28
SD	0.95	0.95	0.98	0.95
COV	0.13	0.14	0.14	0.13
Max	8.70	8.55	8.97	9.97
Min	5.14	4.74	5.23	5.54
Range	3.55	3.93	3.74	4.33

Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	7.13	5.82	7.05	7.52
SD	1.04	1.10	0.89	1.25
COV	0.15	0.15	0.13	0.17
Max	8.35	8.01	8.07	9.97
Min	5.14	4.74	5.82	5.51
Range	3.21	3.27	2.25	3.35

Relationship between shot-put resultant velocity and performance

The strength of the correlation between performance and shot-put resultant velocity is presented in Table D 4. Only correlations of ≥0.5 (strong or above) will be reported below:

- very strong for seating Configurations A and B, for all throws,
- almost perfect for seating configurations A and B, for best throws.

As presented in Table D 8, shot-put resultant velocity was a significant ($p<0.01$) variable for seating Configurations B only, whereby a 0.1 ms^{-1} increase in shot-put resultant velocity would bring about a 0.31 m increase in performance for seating Configuration B.

Shot-put resultant velocity had been eliminated from seating Configurations A, C and D through the stepwise regression process. There was a main effect of the interaction between sitting direction and use of holding pole ($F = 9.47$, $p = 0.03$) on shot-put resultant velocity suggesting that using a holding pole from a front on sitting direction produces greater shot-put resultant velocity, as presented in Table D 9.

Shot-put Angle

As presented in Table 5 8, the differences between the means of all throws and the best throws for shot-put angle were 5% for seating Configuration A, 2% for Configuration B, 1% for Configuration C and 2% for Configuration D, respectively. There was low intra throw variability across all seating configurations with C and D having slightly higher variability than A and B, for all throws and best throws (O'Riordan and Frossard 2020c).

Table 5 8: Angle of the shot-put (in degs) represented by the mean and standard deviation of all throws and best throws, for seating Configurations A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	28.89	30.23	28.87	27.90

SD	8.45	8.51	10.91	11.22
COV	0.29	0.28	0.38	0.40
Max	43.25	45.89	45.21	43.79
Min	11.33	11.11	5.55	5.79
Range	31.93	35.78	39.55	38.00
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	27.44	30.50	29.03	27.31
SD	7.73	9.51	13.00	13.31
COV	0.28	0.31	0.45	0.49
Max	35.54	45.89	45.21	42.51
Min	14.15	15.98	12.59	5.79
Range	21.49	30.91	33.51	35.82

Relationship between shot-put angle and performance

The strength of the correlation between performance and shot-put angle is presented in Table D 5. Only correlations of >0.5 (strong or above) will be reported below:

- very strong for seating Configuration A, strong for Configuration D, for all throws,
- very strong for seating Configurations A and B, strong for Configuration D, for the best throws.

As presented in Table D 8, shot-put angle was a significant ($p<0.05$) variable for all seating Configurations (A, B, C and D), whereby a 1 deg increase in shot-put angle would bring about a;

- 0.17 m decrease in performance for seating Configuration A,
- 0.01 m decrease in performance for seating Configuration B,
- 0.34 m increase in performance for seating Configuration C,
- 0.34 m increase in performance for seating Configuration D.

There were no main effects ($p \leq 0.05$) of sitting direction and use of holding pole for shot-put angle, as shown in Table D 9.

Shot-put Height

As presented in Table 5 9, the differences between the means of all throws and the best throws for shot-put height were 1% for seating Configuration A, 1% for Configuration B, 2% for Configuration C and 1% for Configuration D, respectively. There was similar very low intra throw variability across all seating configurations for all throws and best throws.

Table 5 9: Height of the shot-put (in m) represented by the mean and standard deviation of all throws and best throws, for seating Configurations A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	1.99	1.98	1.97	1.95
SD	0.09	0.08	0.05	0.05
COV	0.04	0.04	0.03	0.03
Max	2.11	2.15	2.09	2.07
Min	1.73	1.80	1.87	1.80
Range	0.38	0.35	0.22	0.27
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	1.98	1.99	1.93	1.97
SD	0.09	0.10	0.03	0.05
COV	0.04	0.05	0.02	0.03
Max	2.08	2.12	1.98	2.04
Min	1.80	1.84	1.89	1.91
Range	0.28	0.28	0.09	0.14

Relationship between shot-put height and performance

The strength of the correlation between performance and shot-put height is presented in Table D 6. Only correlations of >0.5 (strong or above) will be reported below:

- strong for seating Configurations A and B, as well as negligible for Configurations C and D, for all throws,
- Very strong for seating Configuration A, strong for Configuration B, moderate (negative) for Configuration D, as well as low for Configuration C, for the best throws.

As presented in Table D 8, shot-put height was a significant ($p \leq 0.05$) variable for seating Configurations A and B, whereby a 0.1 m increase in shot-put height would bring about a;

- 0.44 m increase in performance for seating Configuration A
- 0.25 m increase in performance for seating Configuration B.

Shot-put height had been eliminated from seating Configurations C and D through the stepwise regression process. There were no main effects ($p \leq 0.05$) of sitting direction and use of holding pole for shot-put height, as presented in Table D 9.

Shot-put Gain

As presented in Table 5 10, the differences between the means of all throws and the best throws for shot-put gain were 8% for seating Configuration A, 1% for Configuration B, 4% for Configuration C and 17% for Configuration D, respectively. There was low intra throw variability (COV <1) for seating Configurations A and C but high intra throw variability (COV >1) for Configurations B and D, for all throws and best throws (O'Riordan and Frossard 2020c).

Table 5 10: Gain of the shot-put (in m) represented by the mean and standard deviation of all throws and best throws, for seating Configurations A, B, C and D. (n = number of throwing trials, SD: standard deviation, COV: Coefficient of variation, Max: maximum value, Min: minimum value).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All Throws	n = 44	n = 44	n = 35	n = 34
Mean	0.24	0.21	0.27	0.23
SD	0.12	0.21	0.21	0.22
COV	0.50	1.00	0.78	0.97
Max	0.47	0.85	0.58	0.59
Min	-0.01	-0.09	-0.13	-0.13
Range	0.48	0.94	0.81	0.82
Best Throws	n = 8	n = 8	n = 6	n = 6
Mean	0.25	0.20	0.25	0.19
SD	0.07	0.25	0.25	0.25
COV	0.27	1.24	1.00	1.30
Max	0.37	0.73	0.58	0.57
Min	0.19	-0.02	-0.09	-0.05
Range	0.18	0.75	0.77	0.53

Relationship between shot-put gain and performance

The strength of the correlation between performance and shot-put gain is presented in Table D 7. Only correlations of >0.5 (strong or above) will be reported below:

- strong (negative) for seating configuration D, for best throws.

There were no main effects ($p \leq 0.05$) of sitting direction and use of holding pole for shot-put gain, as presented in Table D 8 and Table D 9.

5.4 Discussion

The purpose of this study was to identify which seating configuration might have the greatest efficacy on shot-put release variables and performance of elite seated shot-putters. This was informed by the deterministic model for seated shot-put where an analysis of shot-put variables at the release point, referred to as Tier 1, is essential for understanding performance (Figure 3 5).

Low variability was shown across all the variables apart from shot-put gain (O'Riordan and Frossard 2020c). This meant it would be appropriate to conduct intra participant coefficient of variance analysis, which showed low variation across all the variables. For a symptomatic population, such as Paralympic athletes, it would usually be expected to see high inter participant variability. This was not the case in this study, which might be because the participants were elite athletes.

Comparative release variables from previous research involving seated and standing shot-put will be presented initially then each seating configuration will be discussed separately with regards to the release variables. A comparison of relationship to performance for the four seating configurations will be in the interpretation section.

Outcomes

a) Configuration Efficacy

Efficacy was defined earlier as the capacity to impact performance where an efficient seating configuration will increase performance. Clearly, seating Configuration A is the most efficient whilst seating Configuration D appears to be the least efficient of all configurations for both all throws and the best throws, as shown in Table 5 11. Seating Configurations B and C sit in the middle and switch between second and third ranking order for all throws and best throws, respectively.

Table 5 11:. Cross-comparison of mean performance and efficacy of change in performances of seating Configurations A, B, C and D for all throws and best throws. Better refers to the configuration that has the longest mean performance.

Configurations	**Perf**	**A** Front On with Pole	**B** Diagonal On with Pole	**C** Front On with out Pole	**D** Diagonal On without Pole
All throws					
A Front On with pole	7.40	0	-0.27	-0.35	-0.72
B Diagonal On with pole	7.13	0.27	0	-0.08	-0.45
C Front On without pole	7.05	0.35	0.08	0	-0.37

D	Diagonal On without pole	5.58	0.72	0.45	0.37	0
	Better		**3**	**2**	**1**	**0**
	Ranking		**1**	**2**	**3**	**4**
Best throws						
A	Front On with pole	7.50	0	-0.22	-0.04	-0.45
B	Diagonal On with pole	7.28	0.22	0	0.18	-0.24
C	Front On without pole	7.45	0.04	-0.18	0	-0.42
D	Diagonal On without pole	7.04	0.45	0.24	0.42	0
	Better		**3**	**1**	**2**	**0**
	Ranking		**1**	**3**	**2**	**4**

As shown in Table 5 4, the longest mean throwing performance for all throws and best throw came from seating Configuration A (front on with holding pole). The shortest mean throwing performance for all throws and best throws was for seating Configuration D (diagonal on without holding pole). Interestingly, seating Configurations B and C reversed order with B having a longer mean distance for all throws but a shorter distance for the best throw. From an applied perspective, this could be of importance as it is the best throw that influences the competition outcome, and not the mean of all the six attempts on offer.

The coefficient of variation ranged between 0.12 m and 0.21 m for the mean of all throws and between 0.11 m and 0.23 m for the mean of the best throws, so very similar between the datasets. There was low intra throw variability across all seating configurations for all throws and the best throws, with A and B recording slightly higher variability than C and D. The coefficient of variation ranged between 0.12 m and 0.21 m for the mean of all the throws and between 0.11 m and 0.23 m for the mean of the best throws.

Interestingly, only seating Configuration A presented the largest mean values for shot-put vertical velocity and height at Tier 1 (release). This highlights the challenge of throwing for distance and makes the interaction and combination of the shot-put release variables that brings about a better performance of more importance, and not just maximum values. Additionally, it highlights that sound understanding of what the athlete is doing prior to release of more importance.

It was also suggested there were main effects for the front on sitting position and using a holding pole, both enabling favourable performance.

b) Seating configurations and release variables

Release variables for each configuration will be compared to the seated benchmark data discussed in Chapter 3 (Cluster 4), alongside data from standing shot-put, as summarised in Table 5 12 below.

Seating Configuration A

Configuration A involved sitting in a front on direction using a holding pole, which had the highest mean performance thus having the strongest efficacy, for both all throws and the best throws (Table 5 11).

Vertical shot-put release velocities were 3.54 ±1.25 ms^{-1} and 3.34 ±1.24 ms^{-1} for all and best throws respectively. Seating Configuration A had the highest vertical shot-put velocity for all throws but only ranked 3rd for the best throws of all configurations, despite displaying the highest performance for both datasets. This might suggest consistency of performance and thus technique across the participants in this configuration compared to the others. The values were higher for all throws and average for the best throws when compared to Chow, Chae and Crawford (2000) and lower than values found by Frossard, Smeathers and O'Riordan (2007).

Horizontal shot-put release velocities were 5.20 ±0.53 ms^{-1} and 5.24 ±0.55 ms^{-1} for all and best throws respectively which ranked 2nd of all configurations behind seating Configuration D for both cases. However, Configuration D recorded the lowest mean performance for all and best throws, which might suggest that horizontal shot-put release velocity maybe of less importance than vertical release velocity with regards to performance improvement. These values were a lower than those reported by Chow, Chae and Crawford (2000) and much lower than Frossard, Smeathers and O'Riordan (2007).

Resultant shot-put release velocities ranged from 7.21 ±0.95 ms^{-1} and 7.13 ±0.95 ms^{-1} for all and best throws respectively, which again ranked 2nd of all configurations behind seating Configuration D. It appears that the vertical velocity vector component is more important for performance than the resultant with Configuration A and would be a technical aspect for athletes and coaches to consider. These values are a little lower than those reported by Chow, Chae and Crawford (2000) and lower than values found by Frossard, Smeathers, O'Riordan (2007). They were very much lower than values from standing throwing research (Table 5 12).

Table 5 12: Summary of release variable data from seated and standing shot-put research (highlighted by blue column).

	Vertical velocity (ms^{-1})	Horizontal velocity (ms-1)	Resultant velocity (ms-1)	Angle (degs)	Height (m)	Gain (m)
Chow, Chae & Crawford (2000)	3.5 ±1.0 - 3.2 ±1.2	6.5 ±1.0 - 6.6 ±0.1	7.4 ±1.2 - 7.4 ±0.5	23.8 ±6.8 - 27.1 ±6.6	2.15 ±0.01 - 2.18 ±0.22	0.45 ±0.01 - 0.38 ±0.01
Frossard, Smeathers & O'Riordan (2007	3.85 - 5.85	8.01 – 7.90	8.30 – 9.95	25.57 - 32.47	1.70 ±0.47 – 2.39 ±0.26	
Dessureault (1977)			11.4	36.8		
McCoy, Gregor, Whiting, Rich & Ward (1984)			13.2	36. 3		
Alexander, Lindner & Whalen 1995			10.6	37.2		
Mendoza, Nixdorf, Isele & Gunther (2009)			13.28 ±0.22 - 13.83 ±0.24	36.00 ±2.77 - 36.79 ±1.57	2.00 ±0.10 - 2.23 ±0.15	
Oh, Shin, Choi, Jeong, Bae, Lee & Oark (2011)			13.25 ±0.38 - 13.13 ±0.31	34.68 ±2.91 - 35.60 ±1.94	2.10 ±0.11 - 2.02 ±0.11	
Dinsdale, Thomas, Bissa & Merlino (2017)			13.69 ±0.26 - 12.74 ±0.37	36.67 ±3.15 - 36.55 ±3.15	2.15 ±0.09 - 2.03 ±0.1	0.16 ±0.1 - 0.04 ±0.1

Shot-put release angles ranged from 28.89 ±8.45 degs to 27.44 ±7.73 degs, for all and best throws respectively, which were lower than Configuration B in both cases, which might suggest that the front on sitting direction might allow athletes to have more control over the release angle by being able to "stay on the shot-put for longer", as commonly described by coaches. Additionally, the configurations facing front on displayed very similar shot-put release angles 28.89 and 28.87 degs for A and C respectively. This compares to a 3 degs difference in the without holding pole Configurations (C and D), which might suggest that using a holding pole induced more consistent shot-put angle at release. These release angle values were mostly higher than most of those found by Chow, Chae and Crawford (2000), and similar to those found by Frossard, Smeathers, O'Riordan and Goodman (2007). They were much lower than values from standing throwing research (Table 5 12).

Shot-put release height ranged from 1.99 ±0.09 m and 1.98 ±0.09 m for all and best throws respectively, which were very similar to Configuration B. Notably again, Configurations A and B (with holding pole) showed higher and more consistent shot-put heights than C and D (without holding pole). These were much lower than those informed by Chow, Chae and Crawford (2000). These large differences may be accounted for by the rules changes (Table 2 2) where athletes now have to remain seated throughout the entire throwing movement.

There was no real value in comparing to standing throwers due to the obvious differences in release height although they were not too much lower which supports the 75cm height of the throwing frame as being comparative to standing.

Shot-put release gain ranged from 0.24 ±0.12m and 0.25 ±0.07m for all and best throws respectively, recording higher values generally along with Configuration C. Shot-put gain is likely to be largely influenced by both the shot-put height and angle at release, which might suggest that using a holding pole assists the athlete to sit tall thus increasing the release height, influencing the release angle and enabling athletes to reach forward to release past the front of the throwing circle. These values were approximately 50% lower than those reported by Chow, Chae and Crawford (2000), which might be attributed to the rules changes with athletes now utilising stronger and more secure strapping to ensure they stay seated. This could negatively impact on the ability to reach forward upon release. The gain values were greater when compared to standing throwers (Dinsdale, Thomas, Bissa and Merlino 2017), which could mean the athlete is able to reach forward past the front of the circle, by leaning on the strap that is keeping their hips in contact with the throwing frame.

There was low inter and intra throw variation for performance and all shot-put release variables for seating Configuration A. Intra throw variation is regarded as a good measure of reliability (Hopkins 2007). Low variability might suggest good research design efficacy so seating Configuration A is appearing to be a consistent configuration that athlete/coaches should consider when maximising performance.

Seating Configuration B

Configuration B involved sitting in a diagonal on direction using a holding pole and recorded the second highest mean performance of the four seating configurations for all throws but only the 3rd highest for the best throws. This is important from an applied perspective, as it is the best performance of an athlete that influences competition outcomes.

Vertical shot-put release velocities were 3.53 ±1.14 ms^{-1} and 3.51 ±1.34 ms^{-1} for all and best throws respectively, which was similar to Configuration A for all throws but higher for the best throws. This might suggest more consistency of performance across all throws but having the highest vertical release velocity for the best throws does not lead to the greatest performance, which might highlight the complexity of throwing for distance. The values were higher for all and best throws when compared to Chow, Chae and Crawford (2000).

Horizontal shot-put release velocities were 5.95 ±0.78 ms^{-1} and 5.78 ±0.88 ms^{-1} for all and best throws respectively which were the lowest values of all the seating configurations, for both datasets. Again, similar to Configuration A, horizontal shot-put release velocity maybe of less importance than vertical release velocity with regards to performance. Values for Configuration B are noticeable lower than those reported by Chow, Chae and Crawford (2000).

Resultant shot-put release velocities ranged from 5.99 ±0.95 ms^{-1} and 5.82 ±1.10 ms^{-1} for all and best throws respectively, which again were the lowest of all the seating configurations. This might suggest that the vertical velocity vector component is also more important for performance than the resultant for Configuration B, which is similar to Configuration A. Similar trends for the release velocities are being seen for Configurations A and B, which might suggest that using a holding pole is influencing the impact of the vertical release velocity on performance.

Shot-put release angles ranged from 30.23 ±8.51 degs to 30.50 ±9.51 degs, for all and best throws respectively, and were the highest of all seating configurations in both cases. The front on sitting direction, Configurations A and C demonstrated some similarity with regards to release angles. However, there was no real connection between Configurations B and D, both diagonal on sitting directions, which suggests then using a holding pole might have some impact on release angle. These release angle values for Configuration B were towards the upper limit of those found by Chow, Chae and Crawford (2000), and Frossard, Smeathers, O'Riordan and Goodman (2007). They were lower than those from standing throwing research (Table 5 12).

Shot-put release height ranged from 1.98 ±0.09 m and 1.99 ±0.09 m for all and best throws respectively, which were very similar to Configuration A. As mentioned previously, Configurations A and B (with holding pole) showed higher and more consistent shot-put heights than C and D (without holding pole), and were much lower than those reported by Chow, Chae and Crawford (2000). These large dissimilarities may be likely to due to rules changes (Table 2 2) where athletes were able to finish in a more upright position with the earlier research.

Shot-put release gain ranged from 0.21 ±0.21 m and 0.20 ±0.25 m for all and best throws respectively, recording lower values generally along with Configuration D, than Configurations A and C. Shot-put gain is likely to be largely influenced by how far forward the hip (on the throwing side) is in relation to the shot-put release position. In Configurations B and D, the diagonal sitting positions, the hip on the throwing side is clearly further behind the shot-put release position, thus impacting on the release gain.

There was low intra participant variation for performance and all shot-put release variables and low inter participant variation for all release variables apart from release gain, for Configuration B. The former variation measure is regarded as a good measure of reliability (Hopkins 2007). Low variability might suggest good study design efficacy so seating Configuration B could be a consistent configuration that athlete/coaches should consider.

The results of the ANOVA highlighted that a 0.1m increase in release height has capacity to bring a 0.25 m performance increase which is less than for seating Configuration A but is still something to be considered when working on technical throwing aspects for improving performance. Seating Configurations A and B were the only ones to have displayed the importance of release height on performance and it is suggested that using a holding pole to assist with height of release would be an advantage to athletes interested in improving performance.

Seating Configuration C

Configuration C involved sitting in a front on sitting direction without a holding pole and recorded the 3rd highest mean performance of the four seating configurations for all throws but the 2nd highest for the best throws.

Vertical shot-put release velocities were 3.41 ±1.43 ms^{-1} and 3.38 ±1.55 ms^{-1} for all and best throws respectively, and were similar to Configuration D but lower than Configurations A and B, which might suggest that using a holding pole has an influence on this release variable. The values were average for all and best throws when compared to Chow, Chae and Crawford (2000). The ANOVA showed that a 0.1ms^{-1} increase in vertical release velocity would bring a 0.23 m decrease in performance, which is suggesting that the vertical release component maybe less helpful for this seating configuration.

Horizontal shot-put release velocities were 5.00 ±0.77 ms^{-1} and 5.02 ±0.93 ms^{-1} for all and best throws respectively which ranked 3rd of all configurations ahead of seating Configuration B for both cases. These values were much lower than those reported Chow, Chae and Crawford (2000). However, the ANOVA reported a 0.1ms^{-1} increase in horizontal release velocity would bring a 0.16 m increase in performance, which might suggest the importance of the release variable for this configuration.

Resultant shot-put release velocities ranged from 7.02 ±0.98 ms^{-1} and 7.05 ±0.89 ms^{-1} for all and best throws respectively, with similar 3rd place magnitude rankings for horizontal release velocity, with Configuration C just higher than B. It appears that the horizontal velocity vector component is more important for performance than the resultant with Configuration C and might be a technical aspect for athletes and coaches to consider. These values are average when compared to Chow, Chae and Crawford (2000), lower than values found by Frossard, Smeathers, O'Riordan and Goodman (2007), and much lower than values from standing throwing research (Table 5 12).

Shot-put release angles ranged from 28.85 ±10.91 degs to 29.03 ±13.00 degs for all and best throws respectively, which were higher than Configuration D but lower than Configuration B in both cases. Angles were very similar to Configuration A for all throws and a little higher for best throws, but there was more similarity with A, both front on sitting, than the configurations with diagonal on sitting direction. The similarity for Configurations A and C release angles were 0 degs and 5 degs for all and best throws respectively, compared to 8 degs and 12 degs for B and D, possibly suggesting that using a holding pole promotes consistency with regards to shot-put angle at release. These release angle values were towards the higher end when compared to Chow, Chae and Crawford (2000), similar to Frossard, Smeathers, O'Riordan and Goodman (2007), and lower than values from standing throwing research (Table 5 12). The ANOVA displayed that a 1 deg increase in release angle would bring a 0.34 m performance increase so should be of interest for athletes and coaches.

Shot-put release height ranged from 1.97 ±0.05 m and 1.93 ±0.03 m for all and best throws respectively, which were very similar to Configuration D for all throws but a little less for the best throws. This configuration displayed more release height inconsistency between all and best throws compared to the other configurations. However, Configuration C had the 2nd highest performance for the best throws, which might suggest that the release height needs to be lower with this particular configuration to maximise performance. The literature states that release height should be optimised for influence on performance, taking into account release position and angle, which suggests that using a holding pole allows more for this to happen. These values were much lower than those informed by Chow, Chae and Crawford (2000).

Shot-put release gain ranged from 0.27 ±0.21 m and 0.25 ±0.25 m for all and best throws respectively, recording the highest value for all throws, and the same as Configuration A for best throws, suggesting front on sitting configurations may be able to impact on the release gain achieved. These values were approximately 50% lower than those reported by Chow, Chae and Crawford (2000), for reasons previously mentioned.

Seating Configuration D

Configuration D involved sitting in a diagonal on direction without a holding pole. It recorded much lower mean performances of the four seating configurations, for both all and best throws.

Vertical shot-put release velocities were 3.43 ±1.55 ms^{-1} and 3.39 ±1.88 ms^{-1} for all and best throws respectively, and were similar to Configuration C but lower than Configurations A and B, which might suggest that not using a holding pole has an influence on this release variable. The values were average for all and best throws when compared to Chow, Chae and Crawford (2000). The ANOVA showed that a 0.1 ms^{-1} increase in vertical release velocity would bring a 0.22 m decrease in performance, which is suggesting that the vertical release component maybe less helpful for this seating configuration, alongside Configuration C.

Horizontal shot-put release velocities were 5.27 ±0.57 ms^{-1} and 5.48 ±0.89 ms^{-1} for all and best throws respectively, which were the highest of all configurations, yet recorded the lowest performance scores, for both datasets. This might suggest that the horizontal release velocities were too high for throwing long horizontal distances and that some focus should be placed on decreasing horizontal release velocity whilst improving vertical release velocity. This is also demonstrated with the higher performing configurations, A and B, who displayed higher vertical but lower horizontal velocities and having greater efficacy. These values were lower than those reported by Chow, Chae and Crawford (2000). However, the ANOVA reported a 0.1 ms^{-1} increase in horizontal release velocity would bring a 0.12 m increase in performance, which might suggest some importance of the release variable for this configuration.

Resultant shot-put release velocities ranged from 7.28 ±0.95 ms^{-1} and 7.52 ±1.25 ms^{-1} for all and best throws respectively, again recording the highest values of all configurations. It would appear that the higher horizontal release velocity has impacted on this resultant value. Yet, it has been discussed, that it might have a better impact on performance if the vertical velocity component was increased over the horizontal one. These values are towards the higher end to those of Chow, Chae and Crawford (2000), lower than values by Frossard, Smeathers, O'Riordan and Goodman (2007), and much lower than values from standing throwing research (McCoy, Gregor, Whiting, Rich and Ward 1984; Alexander, Lindner and Whalen 1995).

Shot-put release angles ranged from 27.90 ±11.22 degs to 27.31 ±13.31 degs for all and best throws respectively, which were the lowest angles of all configurations, in both cases. Angles were closer in magnitude to Configuration A (no similarity for any configuration aspects) for all and best throws and showed little comparison to Configuration B, a similar diagonal sitting direction. As with the other configurations, release angle values were towards higher end when compared to Chow, Chae and Crawford (2000), similar to those found by Frossard, Smeathers and O'Riordan (2007) but lower than values from standing throwing research where values (Alexander, Lindner and Whalen 1995, McCoy, Gregor, Whiting, Rich and Ward 1984 and Dessureault 1977). The ANOVA displayed that a 1 deg increase in release angle would bring the same performance increase as Configuration C, 0.34m, which makes it possible that not having a holding pole may be a negative influence on performance improvement with regards to release angle.

Shot-put release height ranged from 1.95 ±0.05 m and 1.97 ±0.05 m for all and best throws respectively, which were very similar to Configuration C for all throws but a little less for the best throws, and lower than A and B across both datasets. This configuration also displayed better release height consistency between all and best throws compared to Configuration C. These values were much lower than those informed by Chow, Chae and Crawford (2000).

Shot-put release gain ranged from 0.23 ±0.22 m and 0.19 ±0.25 m for all and best throws respectively, recording similar values generally with Configuration B, both diagonal on sitting positions and less than the front on sitting Configurations A and C. These values were approximately 50% lower than those reported by Chow, Chae and Crawford (2000), for reasons mentioned previously.

Interpretation

Table 5 13 displays the strong (and above) correlations for the shot-put release variables against performance, for all and best throws. The correlation coefficient values, referred to as r, are also displayed within the deterministic models for seating Configurations A, B. C and D, as illustrated in Figure E 1- Figure E 4, for all throws. The Tier 1 only deterministic models for the best throws are shown in Figure D 9 – Figure D 12. Only strong (and above) correlations to performance are highlighted (in pink).

There were similar findings for both datasets except that correlations were even stronger for the latter with some almost perfect (r >0.9) associations present. Resultant and vertical release velocities had the largest r values, with angle and height next and both stronger than horizontal velocity. This might be a little surprising since throwing for distance is associated with displacement in the horizontal direction.

Table 5 13: Shot-put release variables demonstrating strong (or above) correlations with performance (✓) for all and best throws, for seating Configurations A, B, C and D.

	All Throws				**Best Throws**			
Shot-put Release Variable	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Vertical Release Velocity	✓	✓			✓	✓		
Horizontal Release Velocity	✓	✓			✓	✓		✓
Resultant Release Velocity	✓	✓			✓	✓		
Release Angle	✓			✓	✓	✓		✓
Release Height	✓	✓			✓	✓		
Release Gain								✓

Additionally, the high r values for both release angle and height might also impact on the influence of the vertical release velocity, whereby the front on sitting direction and use of the holding pole enables maximal sitting height and angle at release, which then influences the vertical release velocity. Furthermore, seating Configuration A had the highest r value for release height over the other configurations, with a 0.1m increase in release height bringing a 0.43 m performance increase. Any increase of height on release should potentially bring an incremental performance improvement assuming other release variables remain consistent.

It appears that athletes/coaches should focus on the vertical component of resultant release velocity for the greatest impact on performance when throwing from seating Configuration A. The challenging aspect of this from a technical viewpoint is how to focus on increasing vertical velocity only, without affecting horizontal velocity as well. Since resultant release velocity is the combination of both vertical and horizontal components it is the careful manipulation of one over the other that will bring about performance improvements.

The strong pattern of correlation to performance across a number of the key release variables generally suggests that seating Configuration A provides opportunity for the main release variables to be manipulated to bring about a performance increase, which should be considered by athletes and coaches in their choice of seating configuration.

The relationship of the release variables to performance for Configuration B are displayed in Figure D 1 and Figure D 2 and show many similarities to Configuration A in that the highest correlated variables to performance are vertical and resultant velocity. They are then followed in order of correlation strength by horizontal velocity, height and angle, which is a little different to Configuration A, where angle and height superseded horizontal velocity. Again, the associations were stronger for the best throws compared to all throws.

The relationship of the release variables to performance for seating Configuration C are displayed in Figure D 3 and Figure D 4 for all and best throws respectively, and show an obvious decrease in r values compared to Configurations A and B in all variables, apart from release gain. Release angle was the variable with the highest r value (moderate strength) of all the release variables, and the only one to be significant ($p \leq 0.05$).

The relationship of the release variables to performance for seating Configuration D are displayed in Figure D 5 and Figure D 6 for all and best throws respectively. The r values in all variables apart from release gain were lower when compared to Configurations A and B. Similar to Configuration C, release angle could be considered the most impactful on performance, more so for Configuration D compared to C where it was a strong correlation for the former against moderate for the latter configuration. It also had the highest significance ($p \leq 0.01$) of all the release variables.

This suggests that angle is the release variable that has the most impact on performance for Configurations C and D and should be a technical consideration for athletes that use this configuration for training and competition. However, they might want to consider changing to a sitting direction using a holding pole as there were much higher correlations to performance demonstrated across a number and variety of release variables for seating Configurations A and B, both of which utilised a holding pole.

As both Configurations C and D did not use a holding pole it might be suggested that athletes with compromised trunk function may find it more difficult to sit tall and get forward horizontally to influence other release variables such as velocity and height. This would then lead to a technique that releases the shot-put at a higher angle and behind the line of measurement, which was evident from the video footage and is also seen with the higher negative correlation strengths association with release gain for Configurations C and D. Thus, as with seating Configuration C, consideration should be given to changing to a configuration that uses a holding pole, thus increasing the impact of release velocity and height.

Limitations specific to Study 2

The reflective marker placed on the shot-put was a generic one used for joint placement. This marker was often misplaced during the shot-put flight, which meant some trials were unable to be included in subsequent analysis. Using reflective paint to imprint a similar marker onto the shot-put would provide a more effective solution.

5.5. Conclusion

Seating Configuration A was the most consistent showing the highest mean performance. It also showed stronger associations between key release variables, particularly the release velocities and release height. Seating Configuration B also showed consistency of correlation strengths across several release variables. The commonality between seating Configurations A and B was throwing using a holding pole and thus should be considered an important characteristic of the throwing frame design.

This might suggest that seating Configurations A and B enable athletes to have greater control over the release variables that positively influence performance. They may be seen as the configurations that might impact not only on throwing consistency but definitely on better throwing performance. Conversely, it could also be suggested that athletes have less control over the throwing outcome through manipulation of the release variables if using seating Configurations C and D.

These stronger associations might suggest that focusing particularly on some key release variables could improve performance. Thus, coaches and athletes should consider promoting these variables when working on technical aspects of the seated shot-put throw. They also support early throwing theory regarding the importance of release velocity as a key contributor for throwing for distance (Young 2001; Young and Li 2005).

Although it has been highlighted that seating Configuration A and the key release variables of release velocities and release height may be the most important within the context of this study, it should be noted that the focus has been on the shot-put release variables, referred to as Tier 1, as detailed in the deterministic model (Figure 3 5). It does not provide any information on what and/or how the athlete selects and co-ordinates their movement to bring about a maximum performance. To allow for a better understanding of the role that the underlying movement patterns of elite seated shot-putters might play on performance, a dynamical systems theory approach will be followed as proposed by Glazier and Robins (2011) whereby the sequence and maximal linear upper body kinematics will be examined. These are displayed as Tiers 2 and 3 in Figure 3 5 and will form the basis of Study 3 to follow.

The findings from this study which were conducted using the most current rules and taking into account the higher technical constraints now imposed. They confirm what was already known from throwing theory and from previous outdated observational studies. However, this work makes a new contribution by describing quantitatively how the seating configuration (sitting direction and use of holding pole) influences the release variables “for the better (Configurations A and B) or for the worse (Configurations C and D)” to impact performance.

Chapter 6: Study 3

Seating configuration, upper body linear kinematics, and performance of elite seated shot-putters.

Some outcomes of this chapter are presented in the following publication:

- O'Riordan A and Frossard L (2020d) – Variability of linear displacements and velocities of upper body of elite seated shot-putters throwing from different seating configuration, *Mendeley Data, VI,* doi:10.17632/38hvnjy2yj.1.

The content of this chapter will be presented in the following publications:

- O'Riordan A and Frossard L - How seating configuration influences upper body linear kinematics of elite seated shot-putters. To be submitted to Journal of Sports Sciences, May 2021.
- O'Riordan A and Frossard L – Can seating configuration and upper limb kinematics affect performance of seated shot-putters? To be submitted to European Journal of Sport Science, June 2021.

Abstract

Aim: To identify which of four seating Configurations (A, B, C or D), had the most influence on performance of elite seated shot-putters. This was done by exploring the upper body linear kinematics at key phases throughout the throwing movement and the movement characteristics between the phases, and how they impact on performance. ***Methods***: This study focused on 80 linear kinematic variables including duration of throwing phases, horizontal and vertical displacement and velocity for shot-put/hand, elbow, shoulder (on throwing side) and trunk segments from the same four seating configurations. The concept of "efficacy" defined as capacity to impact performance was utilised to differentiate the benefits of seating configurations. A seating configuration was considered efficient when the performance was increased. Additionally, the concept of a "performance zone" was developed corresponding to the rectangle on a segment velocity-time graph defined by the height (estimated instant where the shot-put left the neck in the final delivery phase to the maximum velocity at the point of release) and the width (the same instant of shot-put leaving the neck to the release). ***Results***: Seating Configuration A had a greater number of strong correlations (r >0.5) for the linear upper body kinematic variables in later phases of the throwing motion. In fact, these strong correlations led to this being a strong predictor of better performance. The configurations using a holding pole (A and B) demonstrated taller and narrower performance zones than those without (C and D). ***Conclusion***: The results suggested that a performance zone that is tall and narrow, as opposed to short and wide, is a better predictor of performance. This consolidates findings from Study 2 where a configuration with a holding pole was more beneficial in improving performance.

6.1 Introduction

There has been much research over the years on the kinematic analyses of standing (Olympic) shot-putters (Dessureault 1968; Schaa 2010; Judge, Young and Wanless 2011; Sugamar 2014). Some similarities and inferences have been applied to the technical development of seated shot-put from its standing counterpart (O'Riordan and Frossard 2006; O'Riordan 2015). Of interest is the interaction of athlete technique to their throwing frame and how performance can be positively influenced.

It has been suggested that in standing shot-put the outcome of a throw is largely determined by what happens during the completion phase, i.e. from the power to release positions (Figure 2 3). For instance, 80-90% of the distance thrown can be contributed to by what happens in the time period between front foot touch down (FFTD) and release (Bartonietz, 1996; Turk 1997; Young 2001; Ariel, Probe, Penny, Buijs, Simonsen and Finch 2005; Young and Li 2005).

According to Young (2001), the main purpose of the completion phase is to generate maximal shot-put velocity while releasing at an angle, height and horizontal release distance that relates with high performance outcomes. For seated shot-put, this could be likened to the time period between the athlete changing direction, moving in and out of the power position, and release.

Various biomechanical aspects could contribute to throwing longer distances in standing shot-put (Young 2001). The first one involves the lengthening of the shot-put pathway during the completion phase, however the time duration should be limited (an increased movement speed) thus promoting acceleration, and should be in the direction of the throw (Dessureault 1978; Stepanek 1990; Young 2001; Ariel, Probe, Penny, Buijs, Simonsen and Finch 2005). Although, it is generally understood that the athlete is attempting to release the shot-put at the highest velocity possible it is not clear how the athlete creates the most favourable body positions and movement patterns to generate and apply the largest force possible in the throwing direction.

In addition to the known release parameters described by many (Linthorne 2001; Vecchio, Muller-Karger and Salazar 2012), other critical areas to throwing performance described by Judge, Young and Wanless (2011) include:

- body positions that promote rapid acceleration of the athlete holding the shot-put, referred to as the APSS (athlete plus shot-put system). For seated throwers this could be referred to as the athlete, shot-put and (throwing) frame system (ASFS). It could be argued that as the throwing frame is fixed to the floor it might not have any influence on the body movement, thus contributing to the final release velocity. As the contribution of the throwing frame is not known, it would suggest further the importance of understanding the interaction of the athlete with their throwing frame.
- body positions associated with the rapid deceleration of the athlete just prior to release. This key technical position, as in Figure 2 3, is referred to as the non-throwing side block (NTSB). From a technical viewpoint this is coached as being a rapid bracing of the non-throwing arm, trunk and lower body (for standing athletes), and non-throwing arm (with/without holding pole) and trunk (for those with trunk function) for seated athletes.

These body positions are potentially linked to the concept of trunk-whip (hip-shoulder separation), which relates to "the accelerations of the distal segments as a result of the proceeding acceleration and sudden deceleration of the proximal segments" (Judge, Young and Wanless 2011, p.366). The degree and nature of the hip-shoulder (H-S) separation at the end of the preparation phase, as the seated athlete moves in and out of the power position, could be of importance, and has been discussed in detail for standing shot-putters (Bartonietz and Borgstrom 1995; Godina and Backes 2000) but only in a limited way for seated throwers (Tweedy, Connick, Sayers, Burkett et al. 2012). Of particular importance is the relationship between the hips and shoulders in the transverse plane, with a greater angle potentially increasing trunk whip and extending trunk musculature stretch. This concept is not only significant in shot-put but other throwing and striking events, such as tennis and golf (Joyce, Burnett, Ball and Ball 2010; Hansen, Rezzoug, Gorce, Venture and Isableu (2015).

For seated throwers, the hip-shoulder angle difference just moving out of the power position becomes important as the hips should start moving before the shoulders, generating a greater extension of the trunk, enhancing muscle-tendon unit contraction and/or recoil, and thus producing greater force. The athlete's body position in a seated position might then be of particular significance as the athlete is unable to actively move their hips ahead of the shoulders, as would be expected from a standing athlete. However, the proximal to distal sequencing would still be expected.

Also important to an effective trunk whip in standing shot-put is rapid deceleration of the athlete's non-throwing side just before release, as mentioned previously. This leads to a transfer of momentum from the APSS to the shot-put, resulting in a greater release velocity (Judge, Young and Wanless 2011). In seated shot-put this might refer to the blocking of the non-throwing side with or without the aid of a holding pole. It has also been suggested for standing shot-put that blocking and bracing through knee extension (on non-throwing side) just before release increases momentum transfer to the shot-put by decelerating the horizontal movement of the APSS (Bartonietz 1996). This may correlate for seated throwers, to blocking (with or without a holding pole) with trunk extension on the non-throwing side, so technically may mean a bracing and lifting action is required, which might also influence release height.

The standing shot-put event is considered to be an open kinetic chain movement as the hand is able to move freely when pushing the shot-put into the release (Blazkiewicz, Lyson, Chmielewski and Wit 2016). However, for the majority of the throwing movement the shot-put/hand is in contact with the neck where it sits on top of the shoulder. Thus, it could be argued, particularly for seated shot-put, that the movement is a closed kinetic chain all the time the shot-put/hand is in contact with the neck. Once the shot-put/hand leaves the neck at the start of the pushing action, the movement then becomes an open kinetic chain. Consequently, the point of changing from closed to open chain, could be a critical event in the throwing action.

Another important consideration is the flow and transfer of mechanical energy throughout the kinetic chain as this will contribute to the promotion of acceleration into the release (Blazkiewicz, Lyson, Chmielewski and Wit 2016). Poor co-ordination of the trunk and arm muscles from the power position into the release will result in dissipation of energy through the throwing movement, negatively impacting acceleration into release and ultimately the performance.

High movement variability has been found in athletes with low skill, with a variability decrease in skilled athletes, resulting in greater performance consistency. However, variability often increases again with high skilled athletes due to the flexibility needed to cope with changing circumstances within high level sport, and still achieve favourable performance (Schorer, Baker, Fath and Jaitner 2007, Wilson, Simpson, van Emmerik and Hamill 2008).

Previous kinematic standing shot-put research indicated that athletes are trying to release the shot-put with the highest release velocity possible. However, it is not clear exactly how the athletes select the preferred body positions and movement patterns to be able to generate and apply the largest force possible over the shortest time in the throwing direction, and likely to be individual to each athlete, particularly so for those with functional limitations.

Originally thought of as noise, movement variability is now regarded to be dependent on the co-ordination strategy of the athlete throughout the sporting movement (Bartlett, Wheat and Robins 2007). However, it is claimed that the higher the performance level, the greater its importance (Preatoni, Hamill, Harrison, Hayes, Emmerik, Wilson and Rodana 2013). Elite level athletes appear to demonstrate often repeatable movement patterns. However, small differences are likely to occur between athletes, particularly so for those with compromised function. With elite athletes searching for marginal gain in all areas, these variances could mean the difference between a Gold and Silver medal.

Movement variability is included here as it is a relevant and valuable part of the theory relating to athlete technical differences. However, it will not be discussed in any more detail than the information provided here as it is outside of the scope of this thesis. It is described as:

- the range of coordinative patterns shown whilst performing a movement
- often quantified as the between-trial standard deviation of the movement.

Increasing interest in Paralympic throwing events, including seated shot-put, has led to demand for a better understanding of the biomechanical aspects of these events. Despite the significant advances and popularity in Paralympic sport, the literature review (Chapter 3), highlighted the continued dearth of quality research informing technical aspects of seated shot-put especially under the current WPA rule structure. It further consolidates the reasons why applied biomechanical research is needed in this area and how this study will positively contribute to the essential technical knowledge needed by coaches and athletes to improve performance. It is the application of the research for coaches and athletes that is so important and is lacking.

Thus, because of personal coaching experiences over 20 years and the review of seated throws literature (Chapter 3), the intention of this study is to provide user-friendly recommendations on the biomechanical aspects relating to seating configuration and how it influences performance. The recommendations should assist coaches to make informed decisions regarding seating configuration and other technical aspects. Included within the recommendations will be a deterministic model highlighting the upper body linear kinematic variables that have the strongest correlations to performance, and which could inform coaching decisions on technical interventions.

Study 3 naturally progressed from Study 2, which focused on the shot-put release variables and their influence on performance. The shot-put release variables that demonstrated the strongest associations with performance involved the velocities, height and angle, which consolidated previous throwing related theory (Maheras 1995; Hubbard, de Mestre and Scott 2001; Young and Li 2005; Zhi, Dapena and Bingham 2009). Although consideration of the release variables is essential to the understanding of seated shot-put performance it does not provide any insight on the movement patterns prior to release, and what influence the release favourably.

The deterministic model of seated shot-put for this research (Figure 3 5) was derived from an earlier one created for the same event (Chow, Chae and Crawford 2000), and can be applied to all four seating configurations. The model relates performance to upper body joint linear kinematic variables at key positions throughout the throwing movement as is visually presented in Figure 6 1. Based on the strong associations (where r >0.5) from Study 2 (on shot-put release variables) for the vertical release velocity, it was decided that upper body joint linear kinematics (velocity and displacement) in both vertical and horizontal directions should be investigated. This might be different from other research into throwing which tends to focus on either the resultant or the horizontal components of the implement release and flight (Zhi, Dapena and Bingham 2009)

Another aspect of potential importance to release speed is proximal-to-distal sequencing (Wagner, Pfusterschmied, Tilp, Landlinger, von Duvillard and Müller 2012), described as the time that maximal linear velocities of the segments occurs (Fradet, Botcazou, Durocher, Cretual, Multon, Prioux and Delamarche 2004; van den Tillaar and Ettema 2004). Proximal-to-distal sequencing can only be considered by analysing linear kinematics.

As a result, this study concentrated on upper body linear kinematics (velocity and displacement) variables at key positions of the seated shot-putting movement, including the movement characteristics between the preparatory and delivery phases and their impact on performance, (representing Tiers 1, 2 and 3 of Figure 6 1). Proximal-to-distal sequencing will be viewed by the order of onset as a percentage of the total throw time (%TT) of Tiers 3, 2, and 1 for each of the upper body joints.

The key positions of the throwing movement have been identified previously and relate to Tiers 1, 2 and 3 of the generated deterministic model specific for seated shot-put (Figure 3 5). Their association with key phases and movements are visually presented in Figure 6 1, whereby;

- Tier 1 is the release position and is at the end of the delivery phase
- Tier 2 is the power position and is at the end of the 2nd preparation phase
- Tier 3 is the 1st prep position and is at the end of the 1st preparatory movement.

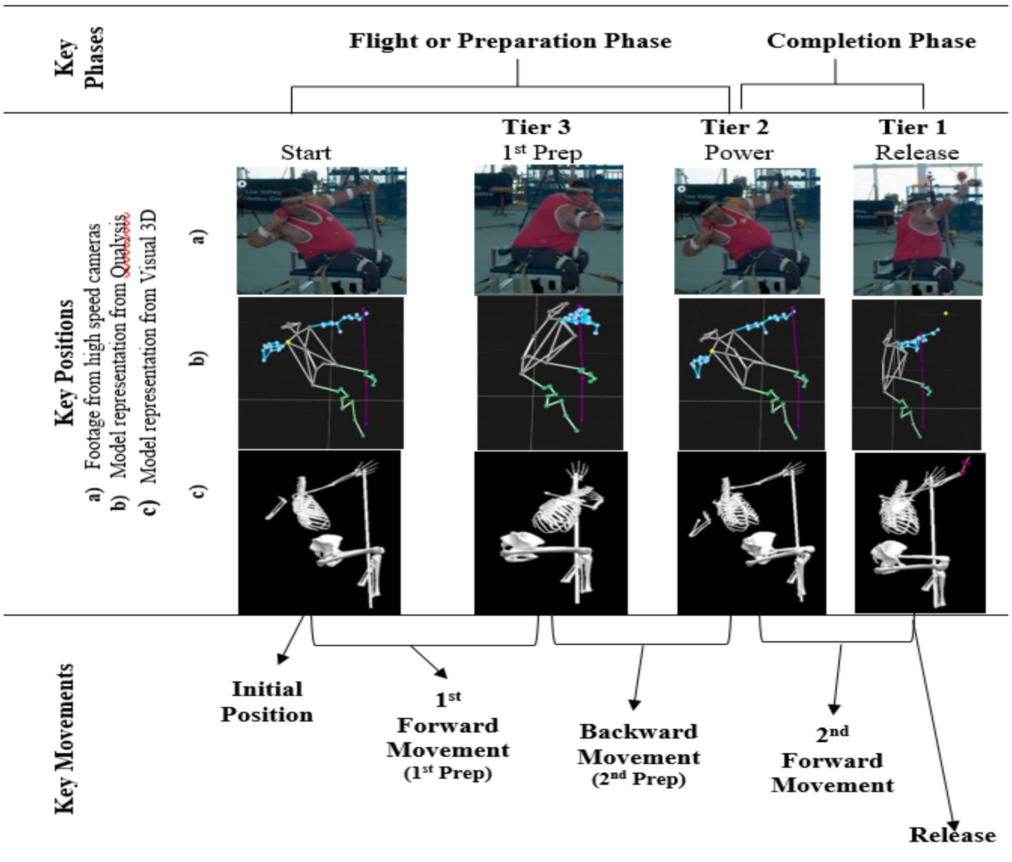


Figure 6 1: Definitions of the key phases, events and movements of the seated shot-putting action with visuals from the high speed camera (a), Qualisys (b) and Visual 3D (c) software.

It is anticipated that this research will be able to define body positions and movement events specific for seated throwing, thus providing a technical model specific to seated throwers that will be useful to coaches and athletes.

Aim, purposes and objectives

The ultimate goal of this study was to improve performance and provide insight for coaches and athletes to enable better evidenced-based decision making when choosing a seating configuration. This would be done by exploring the movement characteristics of upper body linear kinematics throughout the seated shot-put throwing movement, and how they impact on performance.

Consequently, based on the efficacy of the seating configurations found in Study 2, this study will address the following:

- What upper body linear kinematics at Tiers 1, 2 and 3 had the strongest correlations with performance for each of the seating Configurations A, B, C or D?
- How do correlations between linear joint kinematics and performance relate to those of the release variable at Tier 1 (Study 2) and efficacy?
- Does seating configuration affect movement characteristics of the seated shot-putting action?

Aim

The aim of this study was to identify which of the four seating Configurations, A, B, C or D, displayed upper body linear kinematics that could positively impact performance the most.

Purposes

The purposes to this study were to:

- Determine the magnitudes of upper body linear kinematics at Tiers 1, 2 and 3, for each seating configuration.
- Describe the movement characteristics of the linear kinematic variables between the key phases.
- Apply a deterministic model of seated shot-put using correlation coefficient values.

Objectives

The specific objectives were to:

- Establish the relationship between seating Configurations A, B, C and D, upper body linear kinematics, at Tiers 3, 2 and 1, and performance.

6.2 Methods

Essential methodological aspects of data capture and processing used in this study has been detailed previously in Chapter 4. Therefore, only necessary information will be presented here.

Participants

The same eight elite level seated shot-putters as in Studies 1C and 2 participated in this study (37 ±10 years, 1.79 ±0.18 m, 95.33 ±26.02 kg) from classes F55 (n = 3) and F56 (n = 5).

Apparatus

The same experimental throwing frame and tridimensional camera set-up as in Studies 1C and 2 were used in this study (Figure 4 13).

Processing

The data was collected during the same testing session as for Study 1C and utilised the F_10 flight trajectory. A 3D kinematic model of the relevant joints, throwing frame and shot-put was created in Qualisys. The point of release and ten frames post release (the F_10 flight trajectory) were identified as events. The raw 3D kinematic data were exported into Visual3D motion system (Version 4.21, C-Motion Inc., Germantown, Maryland, USA), which was used to further process the kinematic data. All markers' trajectories were filtered using a 4th order Butterworth bi-directional low-pass filter with a cut-off frequency of 8 Hz.

A static model was created, as shown in Figure 6 2. Upper body segments were identified and included trunk, elbow, shoulder and the shot-put/hand complex. Initially the wrist joint was to be utilised but upon initial observation of outputs they were discarded due to tracking challenges, which had not presented as an issue in Study 1C. Instead, the shot-put and hand was considered as a single segment, represented by the shot-put and referred to as the shot-put/hand. This then aligned better to Study 2 whereby the shot-put was the focus when considering the release variables. It was also deemed more relevant to consider the shot-put during the whole throwing action, as ultimately it is the shot-put that is the object that is propelled.

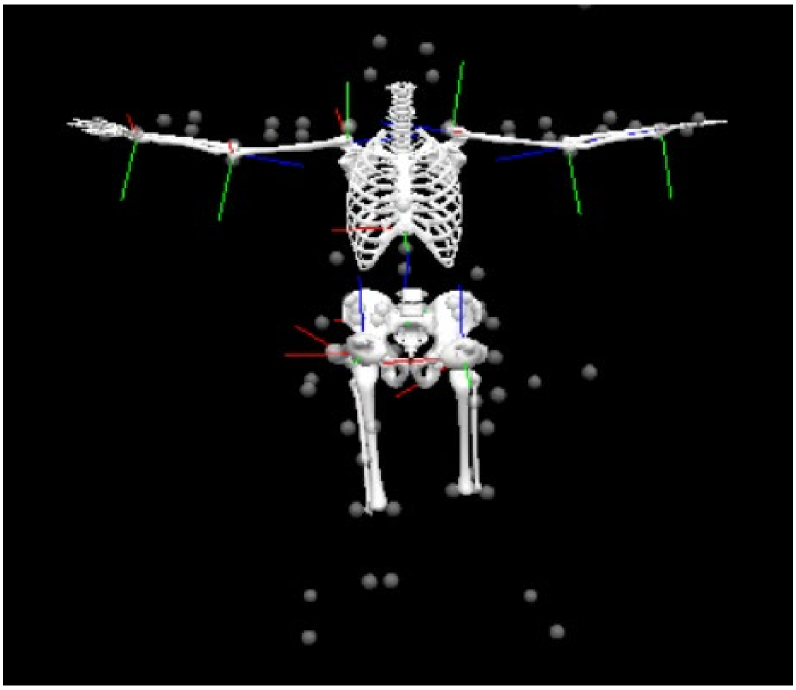


Figure 6 2: Visual representation of the 3D static model created in Visual 3D.

In consultation with the Visual 3D support experts, a more advanced model was recommended than that used in Studies 1 and 2. This was due to the earlier studies only focusing on the point of release, whereas this study would centre on the movement kinematics throughout the throwing action. Details of how the upper body segments were generated are presented in Table D 1.

Once the static model was created it was then applied to the throwing trials to produce visual models, as well as allowing for the associated data to be generated via pipelines. Pipelines allowed for the movement of the upper body segments to be considered through linear displacement and velocity pathways. The joint kinematic variables generated from the pipelines are shown Table 6 1 below.

Table 6 1: Joint kinematic variables generated from pipelines for Tiers 1, 2 and 3. Tier 1 velocity data is the same across both Studies 2 and 3.

		Shot-put/hand	Elbow	Shoulder	Trunk
Tier 1	Displacement	✓	✓	✓	✓
	Velocity	From Study 2	✓	✓	✓
Tier 2	Displacement	✓	✓	✓	✓
	Velocity	✓	✓	✓	✓
Tier 3	Displacement	✓	✓	✓	✓
	Velocity	✓	✓	✓	✓

Data for the whole throwing movement (from start to release) was exported via Visual 3D for each of the upper body segments, normalised and inputted into excel where plot traces were generated for the whole throwing action for shot-put velocity and displacement. This enabled the key positions (Tiers) to be identified from the data (Figure 6 3) in the following way:

- Tier 1 was identified for each trial as being the maximum value throughout the entire throwing movement, at 100% of the throw. The mean was then calculated for all the trials.
- Tier 2 was identified for each trial as being the minimum or maximum value, usually between 50 – 60% of the throw. The mean was then calculated for all the trials.
- Tier 3 was identified for each trial as the minimum or maximum value, usually between 20 – 40% of the throw. The mean was then calculated for all the trials.

Of interest also was the linear displacement and velocity of upper body segments between the movement phases, as shown in Figure 6 3 including:

- Start to Tier 3, the first preparation phase
- Tier 3 to Tier 2, the second preparation phase
- Tier 2 to Tier 1, the completion phase.

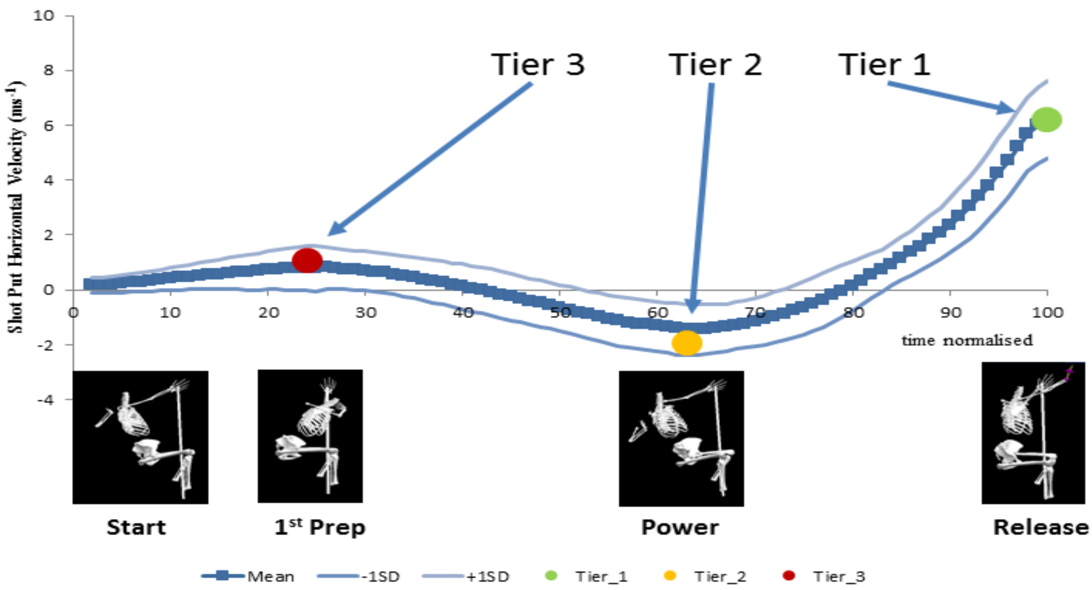


Figure 6 3: Example of graph generated from Visual 3D data of horizontal shot-put velocity against time (normalised) of whole throwing action identifying the key throwing positions.

a) Conditions

Four seating Configurations A, B, C and D were considered, as previously described in Figure 4 8. These were chosen as they were initially identified as the most popular seating configurations currently used by world class seated shot-putters.

b) Datasets

Only one dataset was considered in this analysis, which was all the throwing trials per participant for all seating configurations, referred to as all throws.

c) Variables

As with Study 2, the primary variable was the three-dimensional trajectory of the shot-put over time as determined by the reflective marker placed on the shot-put.

The secondary variables included:

- The dependent variable corresponding to the performance measured from the front of the throwing circle to the nearest landing point of the shot-put.
- The independent temporal, spatial and velocity variables of the trunk, shoulder, elbow, and shot-put/hand (on the throwing side) throughout the throwing movement including:

Temporal

- Duration between Start and Tier 3
- Duration between Tier 3 and Tier 2
- Duration between Tier 2 and Tier 1

Spatial

- Shot-put/hand vertical and horizontal displacement at Tiers 1, 2 and 3
- Elbow vertical and horizontal displacement at Tiers 1, 2 and 3
- Shoulder vertical and horizontal displacement at Tiers 1, 2 and 3
- Trunk vertical and horizontal displacement at Tiers 1, 2 and 3

Velocity

- Shot-put/hand vertical and horizontal velocity at Tiers 1, 2 and 3

- Elbow vertical and horizontal velocity at Tiers 1, 2 and 3
- Shoulder vertical and horizontal velocity at Tiers 1, 2 and 3
- Trunk vertical and horizontal velocity at Tiers 1, 2 and 3.

Statistics

Statistical analyses focused on descriptive statistics, variability and correlation analysis.

a) Descriptive Statistics

The independent variables were presented using basic descriptive statistics as detailed in Table 5 1**,** and included temporal, spatial and velocity variables. The temporal variables concentrated on the duration, in seconds, between the key positions of the throwing movement, as defined in Figure 6 1, from start to release, including;

- the first preparation phase - Start and Tier 3,
- the second preparation phase - Tier 3 and Tier 2
- the completion phase - Tier 2 and Tier 1.

The spatial variables correspond to the mean of the linear displacement (vertical and horizontal), in metres, whilst the velocity variables, in ms^{-1}, concentrate on the average linear velocity (vertical and horizontal). Both are presented at each tier for all the throws, for upper body throwing segments including shot-put/hand, shoulder, elbow and trunk, respectively.

b) Variability

The background to variability analysis has been discussed in Study 2. The coefficient of variation (COV) was calculated by dividing the standard deviation by the mean and a COV >1 was considered high. Inter (throw-to-throw) and intra (participant-to-participant) throw COV were calculated to assess variability between all participants and throwing trials (O'Riordan and Frossard 2020d for inter and intra trial respectively).

c) Individual contribution of secondary variables to performance

The principle underlying correlation analysis was discussed in Study 2. Pearson's correlation analysis was conducted on the data to determine r value, significance and strength of association using the ranges by Hopkins (2002), as shown in Table 5 2. The correlation analysis was undertaken using IBM SPSS Statistics, version 25.

6.3. Results

Only key results will be presented here. Other relevant results appear either in Appendix E or in O'Riordan and Frossard (2020d).

Overview

As detailed in the deterministic model of seated shot-put (Figure 3 5), the Tiers 1, 2 and 3 refer to the positions at release, power and 1st preparatory of the throw, which determine the end points of the delivery, 2nd preparation and 1st preparation throwing phases, respectively. The descriptions of key positions, phases and movements are in Figure 6 1.

Inter and intra throw variability was explored for all linear kinematic variables at Tiers 1, 2 and 3. Inter throw variability was generally low with only 6%, 13%, 12% and 11% of all variables showing high COV (>1) for the shot-put/hand, elbow, shoulder and trunk, respectively. Intra throw variability was higher with 21%, 19%, 38% and 27% of all variables showing as high COV (>1) for seating Configurations A, B, C and D, respectively. However, the majority of high COV instances occurred at Tier 3.

Temporal Variables

Duration of throwing phases

As shown in Table 6 2, the differences between the shortest and longest duration of the throwing phases was 29%, 22% and 6% for the completion, 2nd preparation and 1st preparation phases respectively. There was low intra variability across all seating configurations for all throws, with Configurations A and B recording slightly higher variability than C and D in the earlier throwing phases before showing lower variability in the completion phase.

Table 6 2: Duration of throwing phases (in seconds) represented by the mean and SD of all throws, for seating Configurations A, B, C and D. (COV, Max and Min values, Range and n = number of throwing trials).

	A	**B**	**C**	**D**
	Front On with pole n = 44	Diagonal On with pole n = 44	Front On without pole n = 35	Diagonal On without pole n = 34
Completion Phase				
Mean	0.39	0.43	0.52	0.55
SD	0.09	0.10	0.21	0.30

COV	0.22	0.24	0.40	0.24
Max	0.60	0.69	1.44	0.93
Min	0.25	0.29	0.25	0.36
Range	0.35	0.40	1.19	0.56
2nd Prep Phase				
Mean	0.64	0.68	0.95	0.94
SD	0.26	0.26	0.21	0.26
COV	0.36	0.35	0.22	0.26
Max	1.36	1.39	1.38	1.66
Min	0.35	0.33	0.60	0.50
Range	1.02	1.09	0.68	0.16
1st Prep Phase				
Mean	0.86	0.86	0.82	0.80
SD	0.35	0.34	0.26	0.36
COV	0.41	0.39	0.32	0.46
Max	1.69	1.59	1.36	1.80
Min	0.18	0.29	0.11	0.02
Range	1.61	1.39	1.26	1.68

Relationship between throwing phase duration and performance

The strength of the correlation between the performance and the throwing phase duration is presented in Table E 1. Only correlations of >0.5 (Strong or above) will be reported with the 2nd Preparation Phase duration being the only one to show a strong (negative) correlation to performance for seating Configuration A with significance at $p \leq 0.01$ level.

Spatial variables

Vertical displacement of upper body throwing segments

a) Vertical displacement at each tier

Onset over time

The onset of vertical displacement of the upper body throwing segments at Tier 1 (Release) was considered to be 100% of the throwing time for all seating configurations. As detailed in Table 6 3, for the shot-put/hand, the onset of shot-put vertical displacement at Tier 3 occurred between 33% and 50%, before Tier 2, and between 20% and 26% before Tier 1, across the seating configurations.

For the elbow, the onset of elbow vertical displacement at Tier 3 occurred between 25% and 46% before Tier 2, and between 16% and 35% before Tier 1, across the seating configurations.

For the shoulder, the onset of shoulder vertical displacement at Tier 3 occurred between 38% and 54% before Tier 2, and between 18% and 23% before Tier 1, across the seating configurations.

For the trunk, the onset of trunk vertical displacement at Tier 3 occurred between 36% and 43% before Tier 2, and between 18% and 31% before Tier 1, across the seating configurations

Table 6 3: Mean of onset expressed as the percentage of throwing time (%TT) of upper body throwing segments at Tiers 2 and 3 for seating Configurations A, B, C and D. Tier 1 onset is 100%TT for all segments, n = number of throwing trials).

	A Front On with pole (n = 44) Mean	**B** Diagonal On with pole (n = 44) Mean	**C** Front On without pole (n = 35) Mean	**D** Diagonal On without pole (n = 34) Mean
Tier 2 - Power				
Shot-put/Hand	80	80	66	63
Elbow	84	83	69	65
Shoulder	82	82	80	66
Trunk	82	81	63	69
Tier 3 - 1st Prep				
Shot-put/Hand		30	26	25
Elbow	36	40	38	40
Shoulder	44	35	32	23
Trunk	46	38	32	32

As detailed in Table 6 4 for the shot-put/hand, the difference between the highest and lowest shot-put vertical displacement for all seating configurations was 0.05 m, 0.06 m and 0.02 m at Tiers 1, 2, and 3, respectively. The difference in magnitude of shot-put vertical displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3 respectively was 0.66 m and -0.24 m for Configuration A, 0.69 m and 0.24 m for Configuration B, 0.68 m and -0.19 m for Configuration C and 0.66 m and -0.19 m for Configuration D.

For the elbow, the difference between the largest and smallest elbow vertical displacement for all seating configurations was 0.06 m, 0.08 m and 0.05 m at Tiers 1, 2, and 3, respectively. The difference of magnitude of elbow vertical displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3 respectively was 0.26 m and 0.13 m for Configurations A, 0.24 m and 0.12 m for Configuration B, 0.18 m and 0.05 m for Configuration C and 0.32 m and 0.16 m for Configuration D.

For the shoulder, the difference between the largest and smallest elbow vertical displacement for all seating configurations was 0.05 m, 0.05 m and 0.03 m at Tiers 1, 2, and 3, respectively. The difference of magnitude of elbow vertical displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3 respectively was 0.45 m and 0.28 m for Configuration A, 0.45 m and 0.28 m for Configuration B, 0.35 m and 0.22 m for Configuration C and 0.38m and 0.24 m for Configuration D.

For the trunk, the difference between the largest and smallest elbow vertical displacement for all seating configurations was 0.03 m, 0.03 m, and 0.02 m, at Tiers 1, 2, and 3, respectively. The difference of magnitude of trunk horizontal displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3 respectively was 0.60 m and 0.61m for Configuration A, 0.66 m and 0.60 m for Configuration B, 0.66 m and 0.63 m for Configuration C and 0.65 m and 0.62 m for Configuration D.

Table 6 4: Mean and standard deviation of vertical displacement, expressed in m of shot-put/hand, elbow, shoulder and trunk segments at Tiers 1 (Release), 2 (Power) and 3 (1st Prep) for seating Configurations A, B, C and D (n = number of throwing trials).

	A Front On with pole (n = 44) Mean ±SD	**B** Diagonal On with pole (n = 44) Mean ± SD	**C** Front On without pole (n = 35) Mean ± SD	**D** Diagonal On without pole (n = 34) Mean ± SD
Tier 1 - Release				
Shot-put/Hand	1.24 ±0.26	1.26 ±0.30	1.22 ±0.21	1.19 ±0.29
Elbow	-0.19 ±0.06	-0.16 ±0.08	-0.14 ±0.05	-0.20 ±0.13
Shoulder	-0.36 ±0.10	-0.34 ±0.10	-0.32 ±0.16	-0.33 ±0.08
Trunk	-0.36 ±0.12	-0.36 ±0.10	-0.34 ±0.13	-0.34 ±0.10
Tier 2 - Power				
Shot-put/Hand	0.46 ±0.12	0.46 ±0.12	0.54 ±0.19	0.53 ±0.20
Elbow	0.06 ±0.06	0.06 ±0.08	0.04 ±0.06	0.12 ±0.06
Shoulder	0.08 ±0.05	0.08 ±0.06	0.03 ±0.06	0.05 ±0.11
Trunk	-0.32 ±0.08	-0.30 ±0.05	-0.32 ±0.11	-0.31 ±0.11
Tier 3 - 1st Prep				
Shot-put/Hand	0.61 ±0.15	0.61 ±0.16	0.63 ±0.13	0.62 ±0.16
Elbow	-0.06 ±0.08	-0.05 ±0.09	-0.01 ±0.08	-0.05 ±0.09
Shoulder	-0.21 ±0.09	-0.20 ±0.10	-0.19 ±0.10	-0.19 ±0.09
Trunk	-0.29 ±0.08	-0.30 ±0.06	-0.31 ±0.10	-0.31 ±0.09

b) Progression of vertical displacement over the time

For vertical displacement, similar inter but different intra upper body throwing segments movement patterns were displayed (O'Riordan and Frossard 2020d).

The pattern of vertical displacement for the shot-put/hand is rather consistent across all seating configurations with a 0.2 m vertical displacement difference at the end of Tier 3. This is followed by a downward displacement into Tier 2 before a rapid upward displacement to Tier 1, more so for Configurations A and B, than C and D.

The patterns of vertical displacement for the elbow and shoulder are similar across all seating configurations with a near nil (elbow) and downward (shoulder) vertical displacement at the end of Tier 3. This is followed by an upward vertical displacement into Tier 2 before a rapid downward displacement into Tier 1.

The pattern of vertical displacement for the trunk is consistently fairly flat between -0.3 m and 0.4 m from the start to Tier 1, across all seating configurations with a downward displacement into the release.

c) Relationship between vertical displacement and performance

The strength of the correlation between the performance and vertical displacement of the shot-put/hand, elbow, shoulder and trunk at Tiers 1, 2 and 3 are presented in Table E 2. Only correlations of ≥0.5 (strong or above) will be reported so for the shot-put/hand there was a strong correlation for seating Configuration A at Tier 1. For the elbow there were strong correlations for seating Configuration C at Tier 1 and seating Configuration B at Tier 3. There was a strong (negative) correlation for seating Configuration D at Tier 2 for the shoulder.

For the trunk, there was very strong (negative) correlations for seating Configurations A, C and D at Tier 1, and for seating Configuration B at Tier 1 and Configurations A, B and D at Tier 2. There were also almost perfect (negative) for Configuration D, very strong (negative) for A and strong (negative) correlations for Configurations B and C, at Tier 3.

Horizontal displacement of upper body throwing segments

3, followed by a displacement increase into Tier 2 and finally a rapid decrease into Tier 1.

a) Horizontal displacement at each tier

Onset over time

The onset of horizontal displacement at Tier 1 (Release) was considered to be 100% of the throwing time for all seating configurations. As detailed in Table 6 5, for the shot-put/hand, the onset of elbow horizontal displacement at Tier 3 occurred 35%, 38%, 41% and 39% before Tier 2 and 22%, 21%, 25% and 26% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the elbow, the onset of elbow horizontal displacement at Tier 3 occurred 40%, 41%, 52% and 46% before Tier 2 and 16%, 19%, 16% and 19% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the shoulder, the onset of shoulder horizontal displacement at Tier 3 occurred 41%, 44%, 46% and 46% before Tier 2, and 16%, 16%, 16% and 16% before Tier 1 for seating Configurations A, B, C and D, respectively.

For the trunk, the onset of trunk horizontal displacement at Tier 3 occurred 38%, 38%, 36% and 42% before Tier 2, and 18%, 19%, 29% and 28% before Tier 1, for seating Configurations A, B, C and D, respectively.

Table 6 5: Mean of onset expressed as the percentage of throwing time (%TT) of upper body throwing segments at Tiers 1, 2 and 3 for seating Configurations A, B, C and D. Tier 1 onset is 100%TT for all segments (n = number of throwing trials).

	A Front On with pole (n = 44) Mean	**B** Diagonal On with pole (n = 44) Mean	**C** Front On without pole (n = 35) Mean	**D** Diagonal On without pole (n = 34) Mean
Tier 2 - Power				
Shot-put/Hand	68	69	65	63
Elbow	83	81	84	81
Shoulder	83	84	83	84
Trunk	82	81	61	62
Tier 3 - 1st Prep				
Shot-put/Hand	43	41	34	34
Elbow	43	40	32	35
Shoulder	42	40	36	36
Trunk	44	43	34	30

As detailed in Table 6 6, the difference between the highest and lowest shot-put horizontal displacement for all seating configurations was 0.05 m, 0.06 m and 0.02 m at Tiers 1, 2, and 3, respectively.

For the shot-put/hand, the difference between the highest and lowest shot-put horizontal displacement for all seating configurations was 0.14 m, 0.14 m, and 0.13 m, at Tiers 1, 2, and 3, respectively. The difference in shot-put horizontal displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 1.03 m and 0.62 m for Configuration A, 1.02 m and 0.61m for Configuration B, 0.85 m and 0.58 m for Configuration C and 0.86 m and -0.56 m for Configuration D.

For the elbow, the difference between the largest and smallest elbow horizontal displacement for all seating configurations was -0.04 m, 0.06 m and 0.05 m, at Tiers 1, 2, and 3, respectively. The difference in elbow horizontal displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.39 m and 0.26 m for Configuration A, 0.39 m and 0.28 m for Configuration B, 0.31 m and 0.24 m for Configuration C and 0.39 m and 0.26 m for Configuration D.

For the shoulder, the difference between the largest and smallest elbow horizontal displacement for all seating configurations was 0.04 m, 0.06 m and 0.04 m, at Tiers 1, 2, and 3, respectively. The difference in elbow horizontal displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.51m and 0.46m for Configuration A, 0.45 m and 0.42 m for Configuration B, 0.46 m and 0.39 m for Configuration C and 0.46 m and 0.41m for Configuration D.

For the trunk, the difference between the largest and smallest elbow horizontal displacement for all seating configurations was 0.03 m, 0.06 m and 0.05 m, at Tiers 1, 2, and 3, respectively. The difference in trunk horizontal displacement between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.26 m and 0.36 m for Configuration A, 0.28 m and 0.36 m for Configuration B, 0.21 m and 0.25 m for Configuration C and 0.20 m and 0.26 m for Configuration D.

Table 6 6: Mean and standard deviation of horizontal displacement, expressed in m of shot-put, elbow, shoulder and trunk at Tier 1, 2 and 3 for seating Configurations A, B, C and D (n = number of throwing trials).

	A Front On with pole (n = 44) Mean ±SD	**B** Diagonal On with pole (n = 44) Mean ±SD	**C** Front On without pole (n = 35) Mean ±SD	**D** Diagonal On without pole (n = 34) Mean ±SD
Tier 1 - Release				
Shot-put/Hand	0.68 ±0.20	0.62 ±0.18	0.69 ±0.22	0.64 ±0.24
Elbow	-0.30 ±0.09	-0.26 ±0.08	-0.26 ±0.06	-0.26 ±0.13
Shoulder	-0.16 ±0.06	-0.11 ±0.09	-0.16 ±0.08	-0.13 ±0.11
Trunk	-0.11 ±0.06	-0.12 ±0.0	-0.12 ±0.10	-0.12 ±0.11
Tier 2 - Power				

Shot-put/Hand	-0.25 ±0.11	-0.30 ±0.11	-0.16 ±0.19	-0.22 ±0.18
Elbow	0.09 ±0.10	0.12 ±0.11	0.05 ±0.15	0.12 ±0.10
Shoulder	0.35 ±0.11	0.34 ±0.06	0.29 ±0.10	0.34 ±0.05
Trunk	0.15 ±0.06	0.16 ±0.04	0.09 ±0.12	0.08 ±0.12
Tier 3 - 1st Prep				
Shot-put/Hand	0.46 ±0.20	0.41 ±0.16	0.39 ±0.13	0.34 ±0.19
Elbow	-0.18 ±0.14	-0.16 ±0.14	-0.19 ±0.13	-0.14 ±0.15
Shoulder	-0.11 ±0.15	-0.08 ±0.14	-0.10 ±0.15	-0.06 ±0.15
Trunk	-0.21 ±0.08	-0.21 ±0.06	-0.16 ±0.10	-0.19 ±0.08

b) Progression of horizontal displacement over time

The pattern of horizontal displacement for the shot-put/hand is consistent across all seating configurations increasing from the start into the end of Tier 3, whereby horizontal displacement is between 0.30 and 0.40 m before a steep decrease to between -0.20 and -0.30 m at Tier 2, and finally a sharp increase into Tier 1 (O'Riordan and Frossard 2020d).

The patterns of horizontal displacement for the elbow and shoulder are similar across all seating configurations and follow the opposite patterning to the shot-put with a decrease in displacement from the start into Tier

c) Relationship between horizontal displacement and performance

The strength of the correlation between the performance and shot-put/hand, elbow, shoulder and trunk horizontal displacement for Tiers 1 (release), 2 (power) and 3 (1st Prep) are presented in O'Riordan and Frossard (2020d). Only correlations of >0.5 (strong or above) will be reported so for the shot-put/hand there was a strong (positive) correlation for Configuration D at Tier 2 and strong (negative) correlation for Configurations C and D at Tier 3. For the elbow there were strong correlations for Configuration C at Tier 1 and Configuration B at Tier 3.

Velocity variables

Vertical velocity of upper body throwing segments

a) Vertical velocity at each tier

Onset over time

The onset of shot-put vertical velocity at Tier 1 (Release) was considered to be 100% of the throwing time, for all seating configurations. As detailed in Table 6 7, for the shot-put/hand, the onset of shot-put vertical velocity at Tier 3 happened 46%, 51%, 45% and 40% before

Tier 2 and 31%, 30%, 38% and 40% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the elbow, the onset of elbow vertical velocity at Tier 3 happened 52%, 43%, 38% and 43% before Tier 2 and 26%, 26%, 30% and 33% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the shoulder, the onset of shoulder vertical velocity at Tier 3 happened 50%, 49%, 36% and 40% before Tier 2, and 26%, 30%, 42% and 43% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the trunk, the onset of trunk vertical velocity at Tier 3 happened 45%, 32%, 36% and 35% before Tier 2, and 22%, 33%, 36% and 38% before Tier 1, for seating Configurations A, B, C and D, respectively.

Table 6 7: Mean of onset expressed as the percentage of throwing time (%TT) of upper body throwing segments at Tier 1, 2 and 3 for Configurations A, B, C and D. Tier 1 onset is 100%TT for all segments (n = number of throwing trials).

	A Front On with pole (n = 44)	**B** Diagonal On with pole (n = 44)	**C** Front On without pole (n = 35)	**D** Diagonal On without pole (n = 34)
Tier 2 - Power				
Shot-put/Hand	61	60	62	60
Elbow	64	63	60	66
Shoulder	64	60	58	56
Trunk	68	66	63	62
Tier 3 - 1st Prep				
Shot-put/Hand	24	19	16	20
Elbow	22	30	32	24
Shoulder	24	21	21	16
Trunk	33	35	26	26

As detailed in Table 6 8, for the shot-put/hand, the difference between the fastest and the slowest shot-put vertical velocity for all seating configurations was 0.22 ms^{-1}, 0.54 ms^{-1} and 0.18 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in shot-put vertical velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 4.58 ms^{-1} and 1.36 ms^{-1} for Configuration A, 4.49 ms^{-1} and 1.26 ms^{-1} for Configuration B, 3.62 ms^{-1} and 0.66 ms^{-1} for Configuration C and 3.83 ms^{-1} and 0.65 ms^{-1} for Configuration D.

For the elbow, the difference between the fastest and the slowest right elbow vertical velocity for all seating configurations was -0.33 ms^{-1}, 0.12 ms^{-1} and 0.13 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in right elbow vertical velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.38 ms^{-1} and 0.20 ms^{-1} for Configuration A, 0.65 ms^{-1} and 0.33 ms^{-1} for Configuration B, 0.23 ms^{-1} and 0.18 ms^{-1} for Configuration C and 0.60 ms^{-1} and 0.23 ms^{-1} for Configuration D.

For the shoulder, the difference between the fastest and the slowest right shoulder vertical velocity for all seating was 0.43 ms^{-1}, 0.38 ms^{-1} and 0.22 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in right shoulder vertical velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 2.33 ms^{-1} and 1.15 ms^{-1} for Configuration A, 2.42 ms^{-1} and 1.05 ms^{-1} for Configuration B, 1.92 ms^{-1} and 0.63 ms^{-1} for Configuration C and 1.63 ms^{-1} and 0.62 ms^{-1} for Configuration D.

For the trunk, the difference between the fastest and the slowest trunk vertical velocity for all seating was 0.25 ms^{-1}, 0.14 ms^{-1} and 0.13 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in trunk vertical velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.21 ms^{-1} and 0.13 ms^{-1} for Configuration A, 0.41 ms^{-1} and 0.36 ms^{-1} for Configuration B, 0.26 ms^{-1} and 0.26 ms^{-1} for Configuration C and 0.33 ms^{-1} and 0.29 ms^{-1} for Configuration D.

Table 6 8: Mean and standard deviation of vertical velocity expressed in ms^{-1} of shot-put, elbow, shoulder and trunk at Tiers 1, 2 and 3 for seating Configurations A, B, C and D (n = number of throwing trials).

	A Front On with pole (n = 44) Mean ±SD	**B** Diagonal On with pole (n = 44) Mean ±SD	**C** Front On without pole (n = 35) Mean ±SD	**D** Diagonal On without pole (n = 34) Mean ±SD
Tier 1 – Release				
Shot-put/Hand	3.54 ±1.25	3.53 ±1.15	3.22 ±1.63	3.32 ±1.66
Elbow	-0.49 ±0.49	-0.40 ±0.36	-0.10 ±0.81	-0.43 ±0.59
Shoulder	1.51 ±1.10	1.65 ±1.12	1.48 ±1.06	1.22 ±1.39
Trunk	-0.09 ±0.20	0.13 ±0.18	0.11 ±0.21	0.16 ±0.23
Tier 2 – Power				
Shot-put/Hand	-1.04 ±0.49	-0.96 ±0.42	-0.50 ±0.39	-0.51 ±0.50
Elbow	0.18 ±0.16	0.25 ±0.15	0.13 ±0.10	0.16 ±0.06
Shoulder	-0.82 ±0.52	-0.66 ±0.34	-0.44 ±0.32	-0.51±0.26
Trunk	0.12 ±0.28	0.28 ±0.24	0.16 ±0.22	0.16 ±0.26
Tier 3 - 1st Prep				
Shot-put/Hand	0.32 ±0.28	0.31 ±0.26	0.16 ±0.19	0.14 ±0.21

Elbow	-0.02 ±0.04	0.08 ±0.06	-0.05 ±0.05	0.06 ±0.05
Shoulder	0.33 ±0.40	0.28 ±0.30	0.19 ±0.34	0.11 ±0.32
Trunk	-0.01±0.19	0.09 ±0.15	0.11 ±0.38	0.12 ±0.13

b) Progression of vertical velocity over time

The patterns of vertical velocity for the shot-put/hand and shoulder are rather consistent across all seating configurations with a vertical velocity between 0 and 1 ms^{-1} at the end of Tier 3 (1^{st} prep), into a negative velocity into Tier 2 (power) and finally a rapid increase to Tier 1 (release), more so for seating Configurations A and B, than C and D (O'Riordan and Frossard 2020d).

The pattern of vertical velocity for the elbow is consistent across all seating configurations with a near nil vertical velocity at the end of Tier 3 (1^{st} prep), before a slight decrease prior to an increase into a positive vertical velocity around 0.2 ms^{-1} into Tier 2 (power) before a rapid deceleration into Tier 1 (release).

The pattern of vertical velocity for the trunk is consistent across all seating configurations but follows an undulating pattern into Tiers 3, 2 and 1, which is different to previously seen with the other linear kinematic variables.

c) Relationship between vertical velocity and performance

The strength of the correlation between the performance and shot-put/hand, shoulder and trunk vertical velocity for Tiers 1 (release), 2 (power) and 3 (1^{st} Prep) are presented in Table E 5. Only correlations of >0.5 (strong or above will be reported so for the shot-put/hand there was a very strong correlation for Configurations A and B at Tier 1. For the elbow there was a strong (negative) correlation for Configuration D at Tier 3.

For the shoulder, there was a very strong correlation for seating Configuration B at Tier 1, a strong correlation for Configuration A for Tier 2 and a strong (negative) correlation for Configuration D at Tier 3. For the trunk, there were strong for Configurations A and D for Tier 2 and strong (negative) correlations for Configuration C for Tier 3.

Horizontal velocity of upper body throwing segments

a) Horizontal velocity at each tier

Onset over time

The onset of shot-put/hand horizontal velocity at Tier 1 (Release) was considered to be 100% of the throwing time for all seating configurations. As detailed in Table 6 9, for the shot-put/hand, the onset of shot-put/hand horizontal velocity at Tier 3 happened 39%, 40%, 33% and 32% before Tier 2, and 36%, 36%, 54% and 52% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the elbow, the onset of elbow horizontal velocity at Tier 3 happened 46%, 50%, 43% and 43% before Tier 2, and 30%, 32%, 32% and 38% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the shoulder, the onset of shoulder horizontal velocity at Tier 3 happened 34%, 36%, 33% and 34% before Tier 2, and 39%, 38%, 41% and 43% before Tier 1, for seating Configurations A, B, C and D, respectively.

For the trunk, the onset of trunk horizontal velocity at Tier 3 happened 38%, 39%, 36% and 30% before Tier 2, and 32%, 34%, 41% and 46% before Tier 1, for seating Configurations A, B, C and D, respectively.

Table 6 9: Mean of onset expressed as the percentage of throwing time (%TT) of upper body throwing segments at Tiers 1, 2 and 3 for seating Configurations A, B, C and D. Tier 1 onset is 100%TT for all segments (n = number of throwing trials).

	A Front On with pole (n = 44) Mean	**B** Diagonal On with pole (n = 44) Mean	**C** Front On without pole (n = 35) Mean	**D** Diagonal On without pole (n = 34) Mean
Tier 2 - Power				
Shot-put/Hand	64	64	55	53
Elbow	60	68	68	62
Shoulder	61	62	59	56
Trunk	68	66	58	53
Tier 3 - 1st Prep				
Shot-put/Hand	25	24	22	21
Elbow	23	18	25	19
Shoulder	26	26	26	23
Trunk	30	26	21	23

As detailed in Table 6 10 for the shot-put/hand, the difference between the fastest and the slowest shot-put/hand horizontal velocity for all seating configurations was 0.32 ms^{-1}, 0.83 ms^{-1} and 0.44 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in shot-put/hand horizontal velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 8.13 ms^{-1} and 2.96 ms^{-1} for Configuration A, 6.68 ms^{-1} and 2.66 ms^{-1} for Configuration B, 6.10 ms^{-1} and 1.60 ms^{-1} for Configuration C and 6.39 ms^{-1} and 1.63 ms^{-1} for Configuration D.

Table 6 10: Mean and standard deviation of horizontal velocity expressed in ms^{-1} of shot-put, elbow, shoulder and trunk at Tiers 1, 2 and 3 for seating Configurations A, B, C and D (n = number of throwing trials).

	A Front On with pole (n = 44) Mean ±SD	**B** Diagonal On with pole (n = 44) Mean ±SD	**C** Front On without pole (n = 35) Mean ±SD	**D** Diagonal On without pole (n = 34) Mean ±SD
Tier 1 – Release				
Shot-put/Hand	6.20 ±1.42	5.95 ±1.43	6.00 ±1.26	6.26 ±1.59
Elbow	-0.58 ±0.52	-0.63 ±0.45	-0.52 ±0.54	-0.65 ±0.49
Shoulder	1.54 ±0.93	1.86 ±0.60	1.28 ±1.02	1.66 ±1.28
Trunk	-0.61 ±0.41	-0.61 ±0.49	-0.11 ±0.34	-0.16 ±0.34
Tier 2 – Power				
Shot-put/Hand	-1.93 ±0.88	-1.63 ±0.68	-1.10 ±0.49	-1.12 ±0.55
Elbow	0.28 ±0.25	0.35 ±0.20	0.23 ±0.18	0.29 ±0.09
Shoulder	-0.93 ±0.60	-0.62 ±0.58	-0.58 ±0.44	-0.66 ±0.36
Trunk	0.90 ±0.55	0.90 ±0.39	0.54 ±0.33	0.55 ±0.36
Tier 3 - 1st Prep				
Shot-put/Hand	1.04 ±0.81	0.94 ±0.68	0.60 ±0.56	0.61 ±0.63
Elbow	-0.15 ±0.19	-0.16 ±0.19	-0.08 ±0.09	-0.11 ±0.06
Shoulder	0.52 ±0.54	0.60 ±0.49	0.26 ±0.22	0.46 ±0.30
Trunk	-0.46 ±0.41	-0.56 ±0.45	-0.26 ±0.29	-0.24 ±0.29

For the elbow, the difference between the fastest and the slowest elbow horizontal velocity for all seating configurations was 0.21 ms^{-1}, 0.12 ms^{-1} and 0.09 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in elbow horizontal velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 0.86 ms^{-1} and 0.43 ms^{-1} for Configuration A, 1.08 ms^{-1} and 0.52 ms^{-1} for Configuration B, 0.65 ms^{-1} and 0.31 ms^{-1} for Configuration C and 0.94 ms^{-1} and 0.40 ms^{-1} for Configuration D.

For the shoulder, the difference between the fastest and the slowest right shoulder horizontal velocity for all seating configurations was 0.59 ms^{-1}, 0.35 ms^{-1} and 0.33 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in shoulder horizontal velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 2.46 ms^{-1} and 1.45 ms^{-1} for Configuration A, 2.59 ms^{-1} and 1.32 ms^{-1} for Configuration B, 1.86 ms^{-1} and 0.85 ms^{-1} for Configuration C and 2.42 ms^{-1} and 1.13 ms^{-1} for Configuration D.

For the trunk, the difference between the fastest and the slowest trunk horizontal velocity for all seating configurations was -0.60 ms^{-1}, 0.36 ms^{-1} and 0.33 ms^{-1}, at Tiers 1, 2, and 3, respectively. The difference in trunk horizontal velocity between Tier 1 and Tier 2, and Tier 2 and Tier 3, respectively, was 1.61 ms^{-1} and 1.36 ms^{-1} for Configuration A, 1.51 ms^{-1} and 1.46 ms^{-1} for Configuration B, 0.65 ms^{-1} and 0.81ms^{-1} for Configuration C and 0.61 ms^{-1} and 0.69 ms^{-1} for Configuration D.

b) Progression of horizontal velocity over time

As illustrated in Table E 3, the patterns of horizontal velocity for the shot-put/hand and shoulder are rather consistent across all seating configurations with a horizontal velocity between 1 and 2 ms^{-1} at the end of Tier 3 (1st prep), into a negative velocity into Tier 2 (power) and finally a rapid increase to Tier 1 (release).

The patterns of horizontal velocity for the elbow and trunk are consistent across all seating configurations with a near nil (elbow) and negative (trunk) horizontal velocity at the end of Tier 3 (1st prep), into a positive horizontal velocity into Tier 2 (power) before a rapid deceleration into Tier 1 (release).

c) Relationship between horizontal velocity and performance

The strength of the correlation between the performance and horizontal velocity for shot-put/hand, elbow, shoulder and trunk at Tiers 1 (release), 2 (power) and 3 (1st Prep) are presented in Table E 5. Only correlations of >0.5 (strong or above) will be reported so for the shot-put/hand there were strong for seating Configuration A and B for Tier 1 and strong (negative) correlations for seating Configuration C at Tier 2.

For the elbow there was a strong correlation for seating Configuration C at Tier 1 and Tier 2. For the shoulder there was a strong (negative) correlation for seating Configuration D at Tier 1 and Tier 3. For the trunk, there were strong correlations for seating Configuration C at Tier 1 and Tier 3, and for seating Configurations A and B for Tier 2.

Performance Zone

The horizontal velocity movement graphs (Figure 6 4) demonstrate a crossing of the graphs at two points in the throwing movement. The later crossing point was considered of more importance as it occurs during the completion phase, at an instance prior to release. The crossing occurs when the shoulder and shot-put/hand velocity becomes positive and the trunk and elbow velocity become negative. It is suspected this is a critical part of the throwing movement for influencing performance and was named the "performance zone".

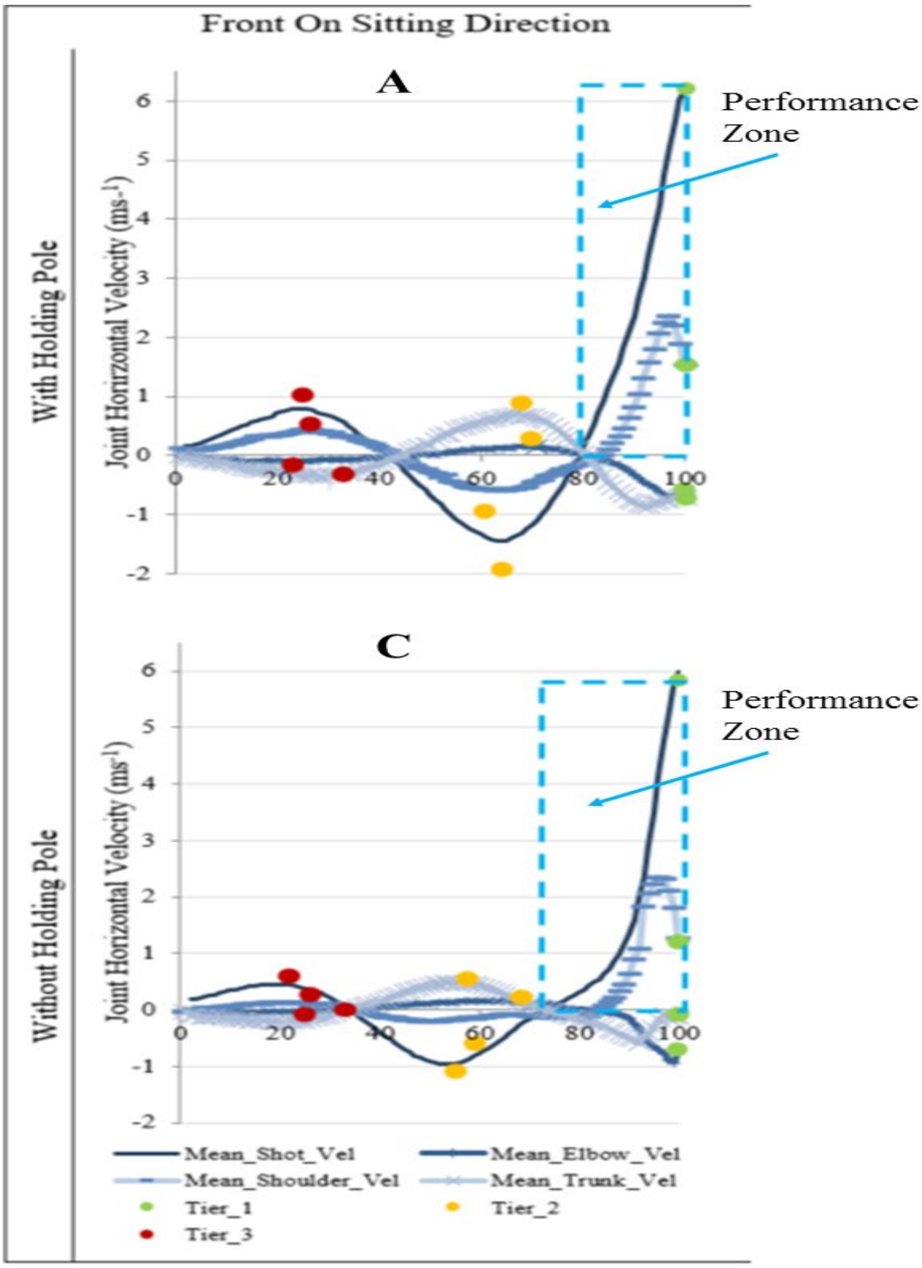


Figure 6 4: Examples of performance zone for seating Configurations A and C.

6.4. Discussion

The aim of this study was to identify which of the four seating Configurations, A, B, C or D, displayed upper body linear kinematics that could positively impact performance the most. This was informed by the deterministic model (Figure 3 5), where an analysis of linear upper body kinematics at and between key positions was considered essential for a better understanding of the movement characteristics of the whole throwing action.

To inform technical aspects of training for athletes and coaches, generic movement patterns of the upper body were considered. Of interest, was understanding the differences in the throwing technique between the seating configurations, and how they might impact the performance. Data variability was considered alongside a comparison of relationship to performance for the four seating configurations. Additionally, the contributions of segmental movement patterns, here denoting to proximal-distal sequencing were considered. The sequence, as suggested by other throwing related research (Urbin, Fleisig, Abebe and Andrews 2013; Wagner, Pfusterschmied, Tilp, Landlinger, von Duvillard and Müller 2014), is likely to go from big and slow to small and fast body segments i.e. trunk, shoulder, elbow, shot-put/hand.

Outcomes

General Observations

All configurations displayed overall similar movement patterns for the displacement and velocity variables. However there appears to be two distinct movement patterns with more intra similarities between seating Configurations A and B, and between Configurations C and D (Figure E 5 – Figure E 8).

The two seating configurations involving a holding pole were Configuration A (front on sitting) and Configuration B (diagonal on sitting). As ascertained in Study 2, the former had the highest mean performance thus having the strongest efficacy, for all throws (Table 5 11 in Study 2) with Configuration B ranked the next highest in efficacy. These efficacy outcomes in themselves might be an important consideration for coaches and athletes when choosing a seating configuration.

Seating Configurations C and D generally showed lower differences in magnitude between the tiers for both displacement and velocity, and more undulating movement patterns between the tiers than Configurations A and B. The former suggests a smaller change in velocity during the movement phases between the tiers, whilst the latter could indicate less control throughout the throwing action. Both aspects are likely to decrease efficiency of the movement. Thus, it could be stated that lower velocity and undulating (less direct) movement between the tiers could be predictors of lesser performance.

The movement patterns for vertical displacement, as shown in Figure 6 5 demonstrate that there is very little change in displacement for both the trunk and elbow, especially from the start of the throw to Tier 2. The shot-put/hand is the only joint that has a positive change in vertical displacement into Tier 3, the release, which means that the other joints are in a lower vertical position on release than at Tier 2 and at the start of the throw

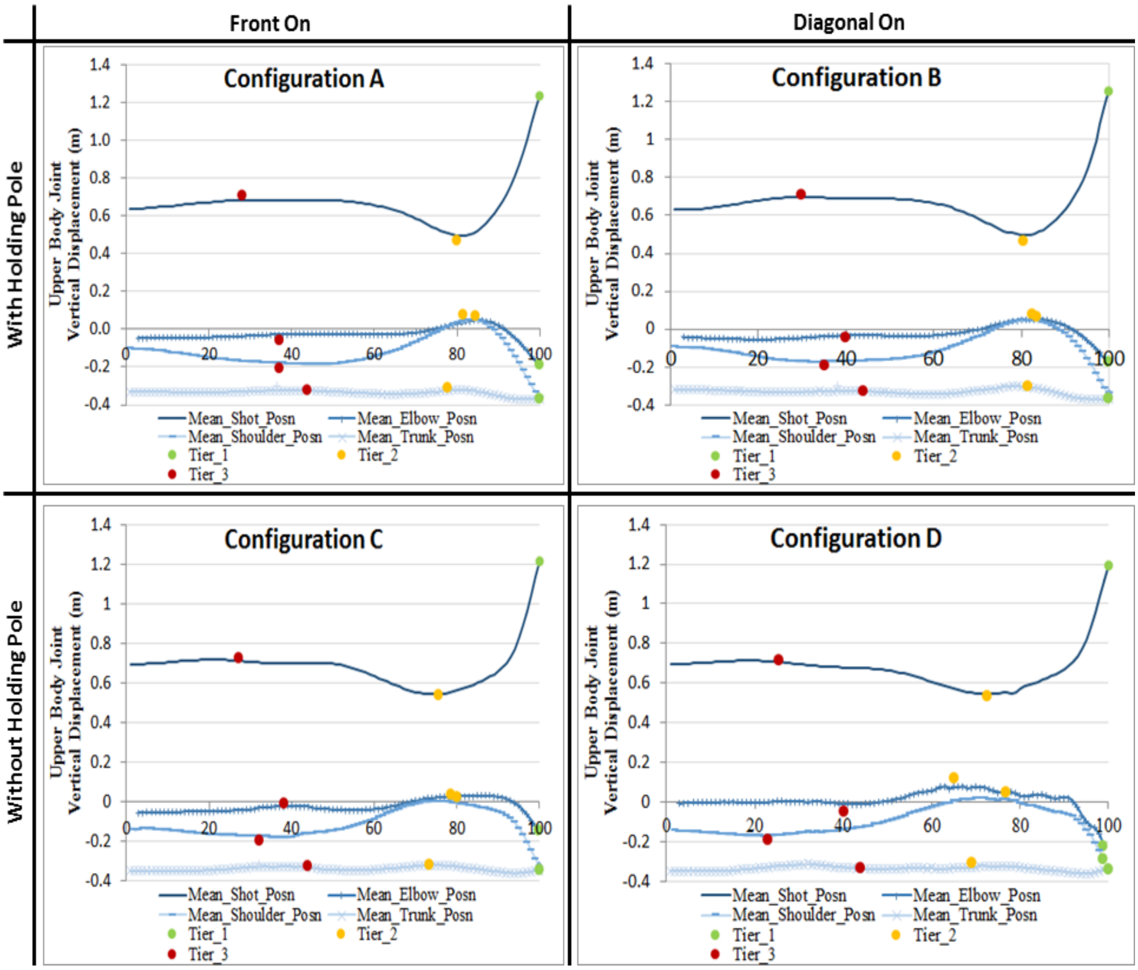


Figure 6 5: Progression of the mean of vertical displacement (all throws), expressed in m, of shot-put/hand, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (1st Prep), 2 (Power) and 3 (Release) for seating Configurations A, B C and D. For ease of clarity, standard deviation not displayed.

All joints have similar movement patterns for horizontal displacement, as shown in Figure 6 6, and as expected due to the direction of the movement in the sagittal plane. There is a forward movement into Tier 3 before a backwards movement into Tier 2 taking place within 80% of the throwing movement. This is followed by a quicker forward progression towards release.

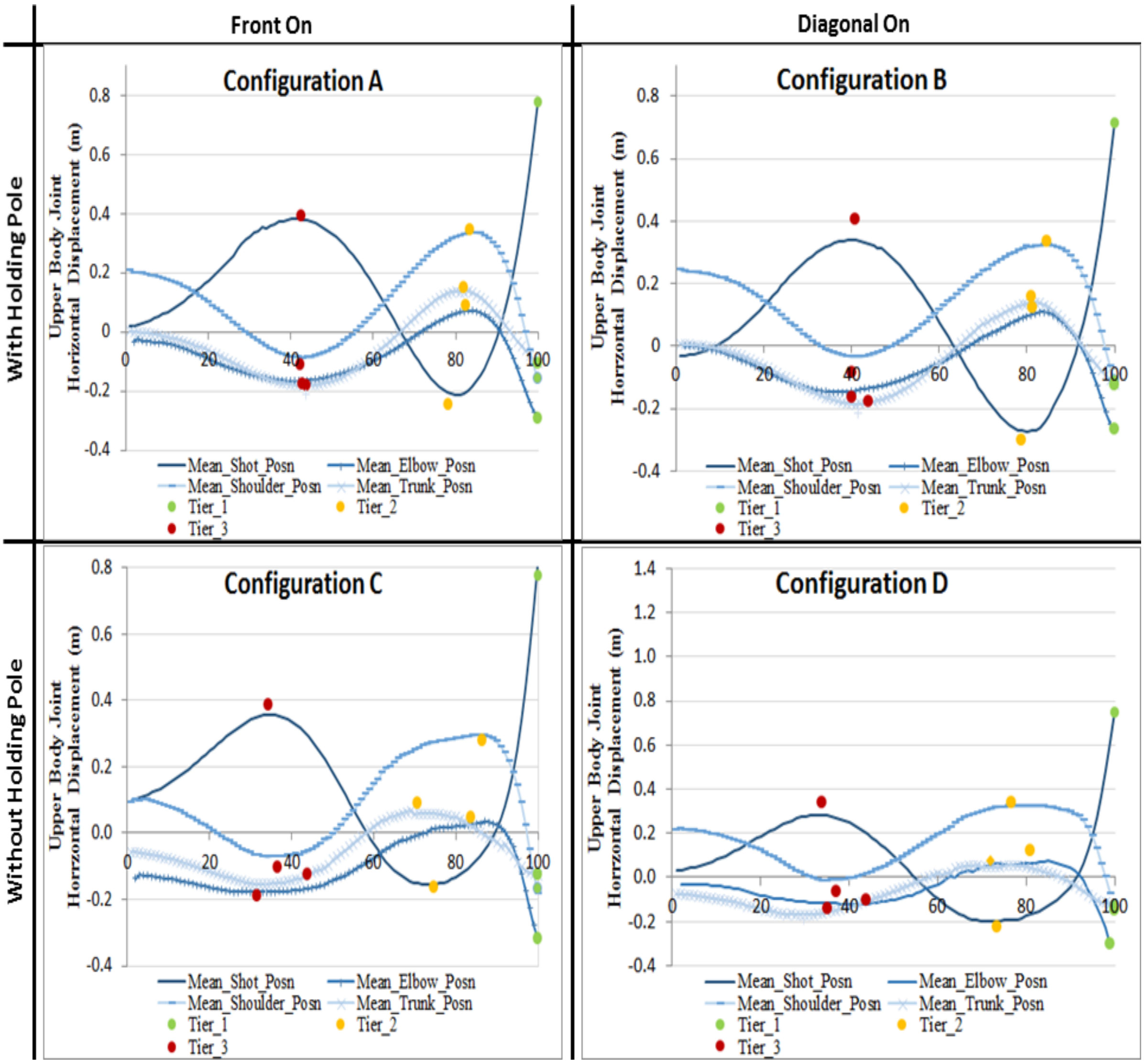


Figure 6 6: Progression of the mean of horizontal displacement (all throws), expressed in m, of shot-put/hand, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (1st Prep), 2 (Power) and 3 (Release) for seating Configurations A, B C and D. For ease of clarity, standard deviation not displayed.

There was generally low inter variability with the shot-put/hand and trunk displaying lower variability than the elbow and shoulder. High inter variability would be expected for symptomatic populations such as those with impairment. There was evidence of some high variability but was still lower than might be expected, likely due to the elite level of the participants. As the coefficient of variability is a product of the standard deviation divided by the mean the higher variability values were because the standard deviation was often higher than the mean value. This could be due to the inconsistencies of the throwing between the participants with some clearly more experienced and with better technical control. The mean and standard deviation profiles can be seen in the throwing movement graphs (Figure E 5 – Figure E 8). The elbow showed the greatest variability of all the upper body joints.

There was lower intra variability for seating Configurations A and B than C and D, with the majority of high coefficient of variation occurring earlier on in the throw at Tier 3. The movement from the start of the throw to Tier 3, the 1st preparation phase, might be a part of the throw for coaches and athletes to consider with a view to improving consistency and contribution to the overall throwing action. However, it is not considered to be the most important position of the throwing, with Tier 2 having more influence on performance (Bartonietz and Borgstrom 1995; Godina and Backes 2000).

Relationship to performance

Table 6 11 displays strong (and above) correlations for upper body linear kinematics against performance, respectively. A strong correlation was also found for Configuration A for duration of the 2nd preparation phase. These correlations are also detailed within the deterministic models for seating Configurations A, B. C and D as illustrated in Figure E 1 – Figure E 4.

Table 6 11: Upper body joint liner kinematics at Tiers 2 and 3 demonstrating strong correlations with performance for seating Configurations A, B,C and D.

		Tier 2				**Tier 3**				
Joint	Variable	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**Total**
Shot-put/ hand	Vertical displacement				✓					1
	Horizontal displacement				✓			✓	✓	3
	Vertical velocity									0
	Horizontal velocity	✓		✓						2
Elbow	Vertical displacement						✓			1
	Horizontal displacement						✓			1
	Vertical velocity								✓	1
	Horizontal velocity	✓		✓						2
Shoulder	Vertical displacement				✓					1
	Horizontal displacement									0
	Vertical velocity	✓							✓	2
	Horizontal velocity								✓	1
Trunk	Vertical displacement	✓	✓		✓	✓	✓	✓	✓	7
	Horizontal displacement									0
	Vertical velocity	✓	✓		✓			✓		4
	Horizontal velocity	✓	✓					✓		3
	Total	6	3	2	5	1	3	4	5	

Only seating Configuration A demonstrated a strong (negative) correlation to performance during the 2nd preparation phase. As this configuration had the greatest efficacy, this might suggest the duration of the phase could be a predictor of better performance. Coaches and athletes might want to pay attention to this phase during technical training with the intention of being slower during this phase, prior to heading into Tier 2 (power position). It might give athletes more time to be able to move into and out of the power position in a technical efficient way alongside pre-tensing key muscles of the trunk and shoulder.

For seating Configuration A, the deterministic model highlights that there are more strong correlations at Tier 2 than at Tier 3 with the trunk showing the largest number of strong correlations of all the upper body joints. Thus, it could be suggested that the greater number of strong correlations in Tier 2 would more likely bring about a better performance since seating Configuration A had the greatest efficacy. The trunk might also want to be a development focus for coaches and athletes at the power position (Tier 2).

Horizontal velocity of the trunk, elbow and shot-put/hand at Tier 2 all have strong correlations to performance for Configuration A. Interestingly, the shoulder is not included here which might mean that it is not playing a favourable role in the movement. It could be something coaches and athletes consider with a view to increasing its contribution in the overall movement pattern. Additionally, vertical velocity at Tier 2 appeared important for the trunk and shoulder but not for elbow and shot-put/hand.

The deterministic model for Configuration B is potentially highlighting that there are a similar number of strong correlations in Tier 3 and Tier 2. This is different to Configuration A which might be mean a predictor of a lesser performance.

However, both Configurations A and B demonstrated similar strong correlations for three of the four trunk kinematic variables for Tier 2 and for trunk vertical displacement at Tier 3. The commonality between these configurations is using a holding pole which could signify that the pole might assist trunk position and movement which in turn might be indicators of better performance.

Elbow displacement (vertical and horizontal) is strongly correlated to performance at Tier 3 for Configuration B but not Configuration A. Since the sitting direction is the difference between these configurations it might imply that sitting in a diagonal on position causes the elbow to be more involved in Configuration B than A but earlier in the movement, which could be a predictor of the lesser performance by the former.

The deterministic model for seating Configuration C is showing the same strong trunk correlations as Configurations A and B but at Tier 3 rather than Tier 2. This suggests that the trunk was more involved earlier in the movement pattern but does not continue into Tier 2 where it is considered to be of more importance for performance (Bartonietz and Borgstrom 1995; Godina and Backes 2000). Overall, Tier 3 had more strong correlations than Tier 2 which could be viewed as indicators of lower performance as is opposite to Configuration A which had greater correlation numbers in Tier 2, and also the greatest efficacy.

For Configuration D, the deterministic model shows the greatest number of strong correlations with performance at Tiers 2 and 3 of all the seating configurations. Additionally, there were no consistency or relationship of correlations between the Tiers. Configuration D had the lowest efficacy and had low correlations to performance for all release variables at Tier 1 (Figure E 4). This might suggest that this configuration is less consistent in terms of technique, whereby athletes are less able to control and move through the earlier phases in the throw to then be able to influence the release variables. Overall, the movement pattern appears more chaotic with little to no transfer of momentum between the body segments.

Configuration A showed the shortest mean duration for the final two phases (completion and 2nd preparation) but longer for the initial phase (1st preparation). The time of the throwing phases reduced from the start of the throwing movement into the release for this configuration, and also had the shortest duration in the completion phase of all the throwing configurations. This is in accordance with throwing principles, suggesting that the throwing phases should subsequently decrease in duration i.e. increase in velocity closer to the release (Vigars 1979; Bartonietz 1994; Judge, Young and Wanless 2011).

Interpretation

Release velocity is claimed to be the main influence on throwing for distance (Young and Li 2005; Bartlett and Robins 2008) and was shown to be the most important predictor of performance in Study 2. Subsequently, both vertical and horizontal velocity movement patterns will be considered in this section, as shown in Figure 6 7 and Figure 6 8.

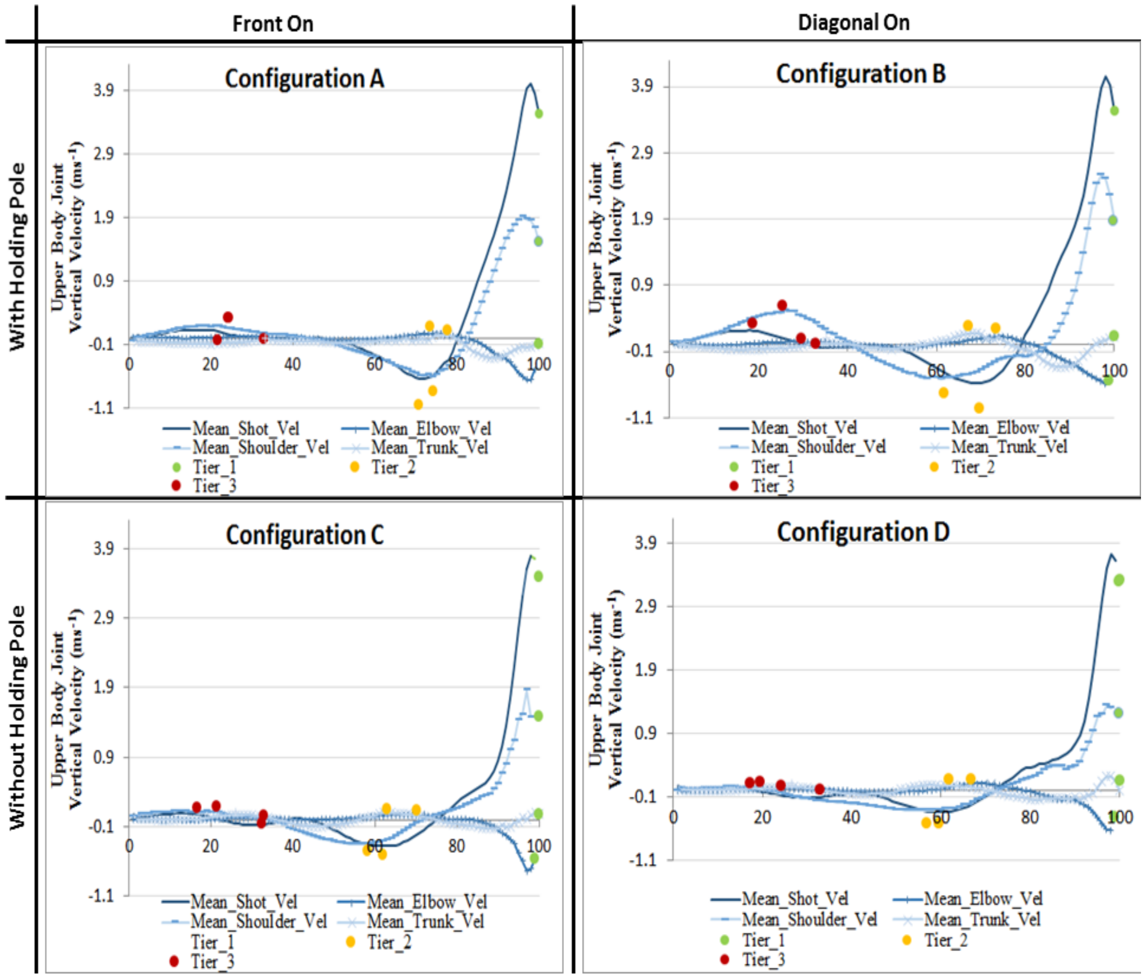


Figure 6 7: Progression of the mean of all throws including magnitude at Tiers 1 (1st Prep), 2 (Power) and 3 (Release) of shot-put/hand, elbow, shoulder and trunk vertical velocity, expressed in ms^{-1}, over the throw time expressed in percentage of throwing time (%TT), for seating Configuration A, B C and D. For ease of clarity standard deviation not displayed.

As mentioned in Chapter 2, the shot-put event can be considered a close kinetic chain movement for the majority of the throw (Blazkiewicz, Lyson, Chmielewski and Wit 2016). This is because the shot-put/hand is held above the shoulder in contact with the neck, in accordance with the rules of the sport (World Athletics 2019). Because the shoulder and shot-put/hand are in close contact they can be considered as one unit, moving together through the throwing movement. This is also demonstrated with Tier 2 onset being very similar for the combinations of shoulder and shot-put/hand, and trunk and elbow for both vertical and horizontal velocity. In both occasions the shot-put/hand complex is ahead of the elbow, shoulder and trunk, which could lead to releasing earlier than desired.

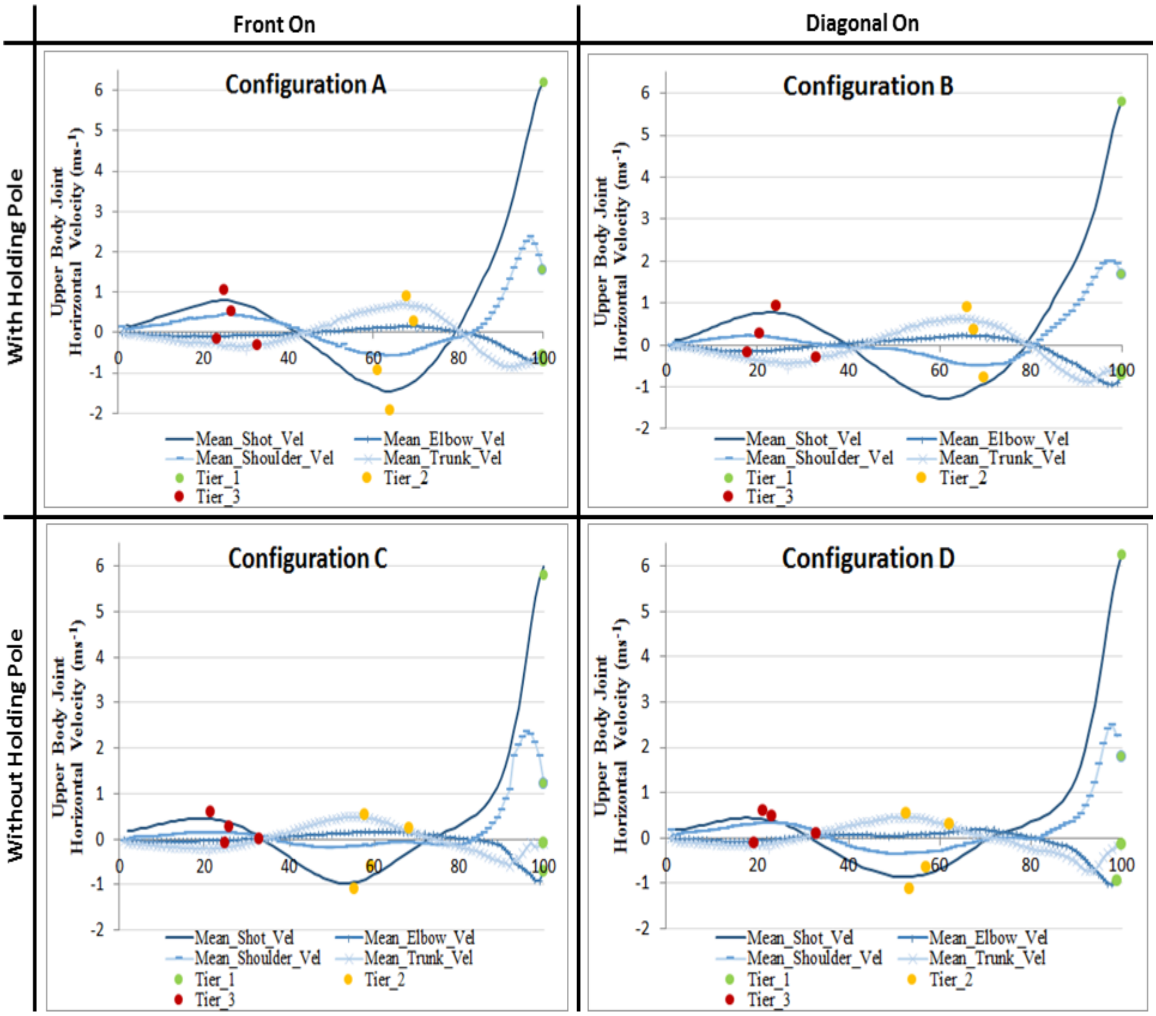


Figure 6 8: Progression of the mean of all throws including magnitude at Tiers 1 (1st Prep), 2 (Power) and 3 (Release) of shot-put/hand, elbow, shoulder and trunk horizontal velocity, expressed in ms^{-1}, over the throw time expressed in percentage of throwing time (%TT) for seating Configuration A, B C and D. For ease of clarity, standard deviation not displayed.

They separate at some point during the delivery phase, between Tier 2 and Tier 1. At this point of separation, the kinetic chain changes from closed to open as the hand is now free to move independently from the trunk and shoulder (Blazevic 2010, Blazkiewicz, Lyson, Chmielewski and Wit 2016). This point of separation is thus likely to be a significant technical point in the throwing movement.

During the closed kinetic chain, the trunk and shoulder involvement is critical because that is where the shot-put is being held. As mentioned in standing shot-put literature other important technical aspects that could contribute to throwing longer distances include lengthening the movement pathway of the shot-put between Tier 2 and Tier 1, the completion phase (Figure 2 3). However, the time duration should be limited thus promoting velocity along the horizontal axis (Dessureault 1978; Stepanek 1990; Ariel, Probe, Penny, Buijs, Simonsen and Finch 2005).

The organisation and sequencing of body segments throughout the kinetic chain might contribute to the promotion of velocity into release, with the co-ordination and activation of the trunk and arm muscles out of Tier 2 of more significance in seated shot-put. Of particular importance will be how a stretch on the trunk and shoulder musculature is generated through enhancing muscle-tendon unit contraction, and how this is controlled by the athlete. This is especially so as a seated shot-putter is unable to actively move their hips ahead of the shoulders, as would be seen in standing shot-put. This could point to the technique employed as the seated shot-putter moves in and out of Tier 2 (the power position) and if they are able to manipulate using their throwing frame to advantage this.

A consideration might be if the holding pole could assist with any pre-tensing of the trunk and shoulder muscles by using it as a fixed point to lever away from with the non throwing arm, thus creating eccentric contraction of the muscles, as seen in the power position (Figure 4 5). However, the lack of trunk control is an important consideration for those with lower lumbar spinal injury, and what contribution the trunk actually plays in the throwing movement.

The elbow is the next joint in the kinetic chain, and generally has a passive role as it is a fixed point just keeping the shot-put into the neck. The rules state that the shot-put has to be in contact with the neck throughout the movement, and the elbow plays a role in enabling this. Consequently, the elbow is not contributing a great deal to the throwing movement in the early phases, which is demonstrated in Table 6 6 and Figure 6 7 where the elbow is producing very little velocity.

However, the movement pattern may not tell the full story of the elbow's contribution due to the often high variability seen as a consequence of the standard deviation regularly being larger than the mean. This might suggest that some participants have more control of the elbow whilst others have less. The contribution of the elbow should increase as it assists in speeding up the shot-put/hand at the point of separation away from the shoulder.

The athlete's ability to promote rapid elbow extension at the time of separation should support in promoting velocity of the shot-put/hand into the release, aligning with throwing principles of contributing to maximum throwing power at this point (Pagani 1981; O'Shea and Elam 1984). Thus, the elbow positioning whilst holding the shot-put into the neck becomes important, alongside the co-ordination of its movement timing in relation to those joints ahead of it in the kinetic chain i.e. the trunk and shoulder.

For this study, a rectangle was formed at the point of crossing of the graphs to the maximum release velocity of the shot-put/hand. This rectangle might be one way to visually represent a key part of the throwing movement and was known as the performance zone, as shown in Figure 6 4. It is proposed that this is the point where the kinetic chain changes from closed to open i.e. the point that the shot-put/hand leaves the neck.

It is the ratio of the duration between the point of change in kinetic chain status and the shot-put/hand velocity at Tier 1 that is of interest. Similar shaped performance zones with a tall and narrow rectangle were displayed for seating Configurations A and B, whilst Configurations C and D displayed shorter and wider performance zones, as shown in Figure 6 4. The main difference between the shapes of the performance zones is determined by the length of time from the shot-put leaving the neck to the point of release.

Since seating Configurations A and B had greater mean performance and better efficacy to performance than Configurations C and D, it could be stated that a long and narrow performance zone is a predictor of better performance. Coaches and athletes should recognise this when selecting a seating configuration.

The shape of the performance zone could then result in a better understanding of the final delivery technique, with the role of the elbow in this part of the throwing movement becoming very important. A technical focus for coaches and athletes might be considering how much force can be applied to the shot-put by the strong concentric contraction of the triceps brachii muscles in the throwing direction, at the instance of open kinetic chain. Additionally, it would appear that by delaying the point of open kinetic chain close to the release, will result in an increase in efficacy.

Limitations specific to Study 3

Throwing momentum is influenced by the summation of external contact forces. Since the 2014 rule change, the number of contacts athletes have with the throwing frame has been reduced. The athlete has now to remain seated throughout the whole throwing movement. Thus, performances maybe influenced less by the reaction forces and moments applied by the lower limbs on the throwing frame than previously. However, it may be likely that external forces with the holding pole may have increased in opposition. Further understanding of the relationship between performance and external forces was restrained by the limitations of this study.

Despite the relevance of angular kinematics in many sporting activities, no angular kinematic data was included in this thesis. The potential influence of focusing on angular motion is based on earlier research from standing shot-put which regarded the movement as involving more rotation earlier in the throwing motion. However, for seated shot-put the movement is mostly linear up until the final delivery phase. A deliberate decision was made to involve a much more in-depth analysis of linear kinematics as this was considered to be more crucial and has received less attention. Thus, angular kinematic analysis was beyond the scope of this thesis.

The role of the trunk in the throwing movement for athletes with spinal dysfunction and the co-ordination of elbow involvement in the final delivery would be better informed with the use of EMG. The comparison of performance between classification and gender was not included and should be considered in future longitudinal studies.

6.5 Conclusion

The sequential transfer of mechanical energy throughout the kinematic chain has been shown to be an important criterion for shot-put performance (O'Shea and Elam 1984; Bartlett and Robins 2008; Judge, Young and Wanless 2011; Blazkiewicz, Lyson, Chmielewski and Wit 2016). The performance of seated shot-putters relies on the sequencing of the trunk, shoulder and elbow and their role in transferring maximum velocity to the shot-put/hand. Of interest is the role of the elbow at the point where the kinetic chain changes from closed to open chain, i.e. when the shot-put leaves the neck on its final movement into the release (Tier 1). A forceful concentric contraction of the triceps brachii resulting in a more efficient elbow extension along the horizontal axis might enable a higher horizontal velocity of the shot-put/hand at release.

Additionally, delaying the instance of when the shot-put leaves the neck would positively influence the shape of the performance zone, and ultimately performance. It is known that rapid deceleration of an athlete's non-throwing side just before release increases momentum transfer to the shot-put by decelerating the horizontal movement of the athlete plus the shot -put system (Bartonietz 1994; Judge, Young and Wanless 2011). If the point of shot-put leaving the neck takes place at or just after the bracing of the non-throwing-side, then momentum transfer to the shot-put should be enhanced. For seated shot-putters, this bracing could be actioned either with or without a holding pole.

From Study 2, it was shown that Configurations A and B had greater efficacy than Configurations C and D. Their performance zone shapes are thus predictors of better performance, with the recommendation of achieving a long and thin rectangular zone. The shape of this zone also relates to the velocity profiles into the release which were again greater for Configurations A and B. It appears that a seating configuration that utilises a holding pole would be advantageous to better performance of seated shot-putters. Coaches and athletes might want to consider utilising such a configuration for improving performance.

Chapter 7: Findings, Outcomes, Limitations and Future Directions

7.1 Introduction

This chapter presents the key findings, outcomes, limitations and future directions of this research. A main overall aim of the research was to investigate the interaction between the seated shot-putter and their throwing frame. The four most popular seating configurations were considered with a view to informing which configuration might positively impact on performance the most. For this to happen, both the release variables and the movement characteristics prior to the release were considered, as they potentially both had technical implications.

As the number of 3D analyses on seated throwers is limited (n = 4), it was considered necessary to develop the methodology prior to the main data collection. The methodological development took the form of three feasibility studies involving elite seated shot-putters (see Study 1). Specific focus was given to the number and placement of the joint reflective markers and the number of cameras needed to capture the whole throwing movement. Of particular interest was the viewing and identification of the left and right ASIS markers with participants that have some trunk dysfunction and less muscle definition in the lower abdomen area. This was important so that a pelvis model could be created, allowing for trunk kinematics to be considered. The results showed that by increasing the number of cameras to 20 and using larger joint reflective markers for the ASIS joint centres, they were then in view throughout the whole throwing movement. There were also issues with the tracking of the hand segment. Thus, the shot-put and hand were considered as a solid segment and used in subsequent studies instead and referred to as the shot-put/hand.

Due to the applied nature of this research, the point of release and the duration of parabolic flight were considered in detail to ascertain the accuracy between the calculated and manually measured performance (see Study 1C). The study findings are not only relevant to seated shot-put but should inform other research that involves parabolic flight. Once the parabolic flight duration had been examined it was then utilised in the subsequent Study 2 and 3.

Shot-put release variables were determined across the four seating configurations in Study 2. These release variables are the only ones to be reported since the current WPA seated shot-put rules were implemented in 2014. This study was also able to provide insight into which of the seating configurations had the greatest efficacy. The release variables for the four seating configurations were also correlated with performance to ascertain which of the variables might have the greatest impact.

In Study 3, the upper body linear kinematics of elite seated shot-putters through the movement phases of the throw and their subsequent influence on the release variables and performance were explored. In particular, the linear displacement and velocity of upper body joints, including the shot-put/hand were generated. Whole values were generated at Tiers 3, 2 and 1 along with the movement patterns for the 1st preparation, 2nd preparation and completion phases (Figure 6 7 and Figure 6 8). A performance zone was identified, and its shape was considered an important predictor of performance (Figure 6 4).

7.2 Key findings

It was anticipated that the evidence from this research could inform technical training guidelines for coaches, athletes and other interested parties. Therefore, a goal of this research was to provide a novel contribution to the area of biomechanics in terms of para specific kinematic analysis that could influence performance of elite athletes.

The key findings were:

- A comprehensive review of seated throwing literature showed that there was limited 3D kinematic analysis on seated shot-putters, which impacted both technical and throwing frame aspects.
- There were limited applied recommendations that could be used by coaches, athletes and other practitioners.
- The feasibility studies of Study 1 highlighted the challenges of measuring 3D kinematics of seated shot-putters. This included ensuring the reflective markers of the pelvis would be visible throughout the throwing movement. This was particularly important for seated athletes with lumbar spinal dysfunction, and thus of significance for the classifications involved in the research.
- Study 1 also identified issues with the wrist/hand segment. This was solved by considering the shot-put/hand as a solid segment and was considered more relevant as it is the shot-put that is ultimately thrown.

- It was shown that using a parabolic flightpath that concluded at the point of release produced release variables with a large degree of error when calculated performance was compared to manually measured performance.
- A flightpath involving 10 frames post release presented much less error when comparing calculated to measured performance.
- Seating Configuration A had the greatest efficacy alongside the greatest number and stronger correlations to performance for the release variables. This was followed by seating Configurations B, D and C.
- The seating configurations that used a holding pole (A and B) showed similar results with regards to efficacy together with the number and strength of correlations of release variables to performance (Figure 7 1). It was evident they were better than those configurations that did not use a holding pole (C and D) for improving performance.
- Seating Configuration A had a greater number of strong correlations for the linear upper body kinematic variables in Tier 2 than 3. Due to its efficacy, having a greater number of strong correlations in Tier 2 than Tier 3 was considered a predictor of better performance.
- A performance zone was proposed to be the point where the shot-put left the neck in the final delivery phase. It is anticipated that a performance zone that is long and narrow, as opposed to shorter and wider, is a better predictor of performance (Figure 6 4).

7.3 Outcomes

This section contains the original contribution to knowledge of seated shot-put, and the key applications for coaches and athletes to consider with a view to influencing performance i.e. the real-world impact.

There is currently little evidence-based technical insight for the coaching of seated shot-putters. It is difficult to make technically informed coaching decisions without such evidence. This research provides some insight for such coaching decisions, particularly around performance improvement. As a practicing seated throwing coach for many years, I really wanted to provide technical insight for other coaches and athletes on seating configuration and how it impacts performance, and so this became a main intention of this PhD.

The original contributions for knowledge from this thesis are suggested to be:

- A literature review, including systematic search of all seated throwing related research. In addition to providing a better understanding of all the current literature on seated throwing, it also highlighted gaps in the literature.
- An updated deterministic model since the WPA rule change in 2014, based on the recommendations from the literature review, which also informed the study design.
- The model showed the release and linear upper body kinematic variables that had strong correlations to performance for seated shot-putters. This provided a visual representation for coaches and athletes to utilise (Figure 7 1 - Figure 7 4).
- A clear technical breakdown of key positions and phases specific to seated shot-put was provided.
- Assessed error of differing parabolic flight durations for calculated against measured performance. This was important to assure the accuracy and validity of the release and linear kinematic variables.
- Representation and descriptions of linear upper body movement profiles for the differing seating configurations.
- Recommendations for preferred seating configurations, based on performance efficacy and correlations to performance.

Practical implications

To showcase how the study outcome could be shared with the main stakeholders i.e. the athlete participants and their coaches, they were provided with a biomechanical report soon after the data collection testing day. The report was intended for their use only and was not made available to the public. The data was produced via Qualisys programme and an example is shown in Appendix B5.

By correlating the release and linear kinematic variables to performance, some context is provided to coaches to help understand which aspects of the seated shot-putting movement might influence performance. Highlighting the variables that have a strong correlation to performance within a visual representation provides a tool for coaches to utilise when considering technical changes, as shown in Figure 7 1 - Figure 7 4 below.

Seating Configuration A

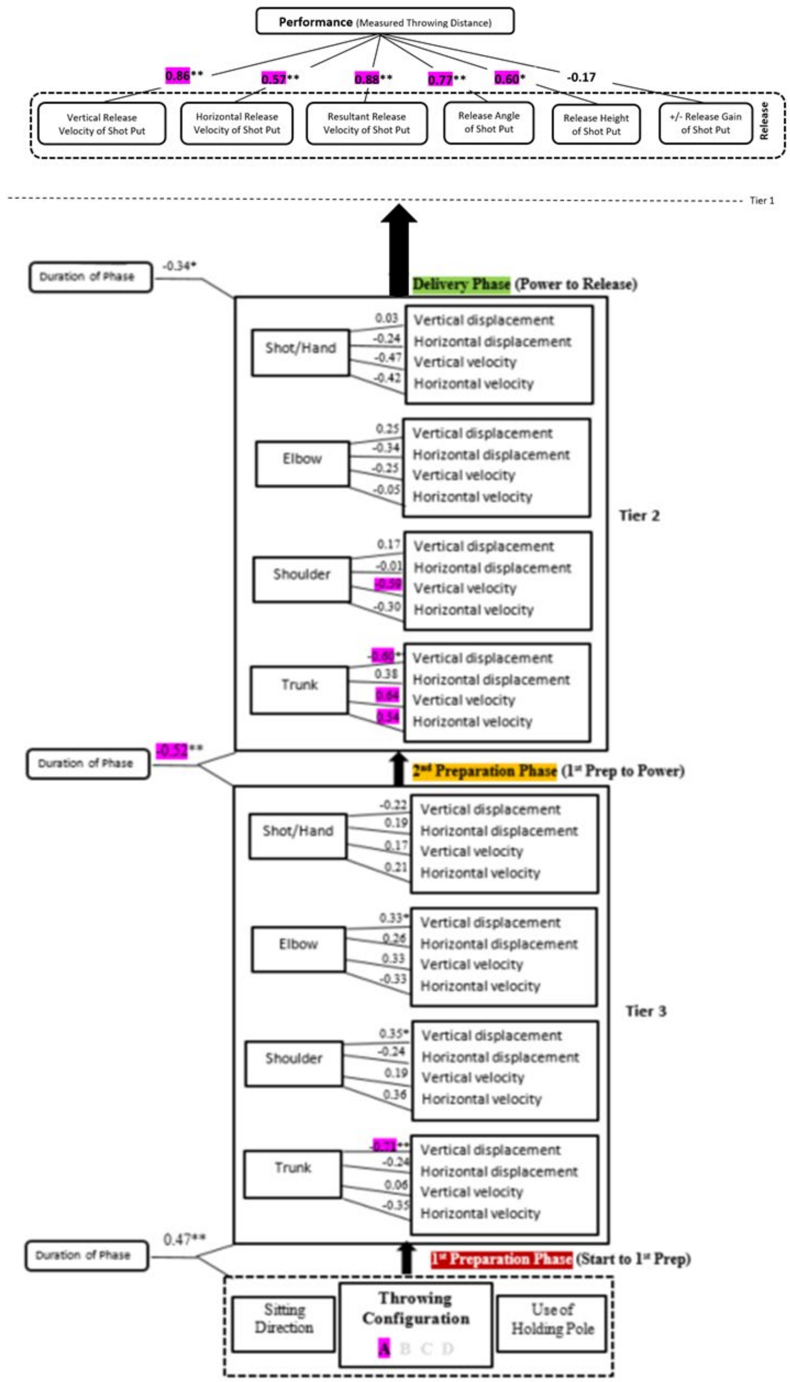


Figure 7 1: A visual representation showing Tiers 3, 2 and 1 of the deterministic model for seating Configuration A, showing the Pearson's correlation r values and level of significance (two-tailed) between key variables and performance for **all** throws. Only strong correlations (>0.50) are highlighted in pink. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

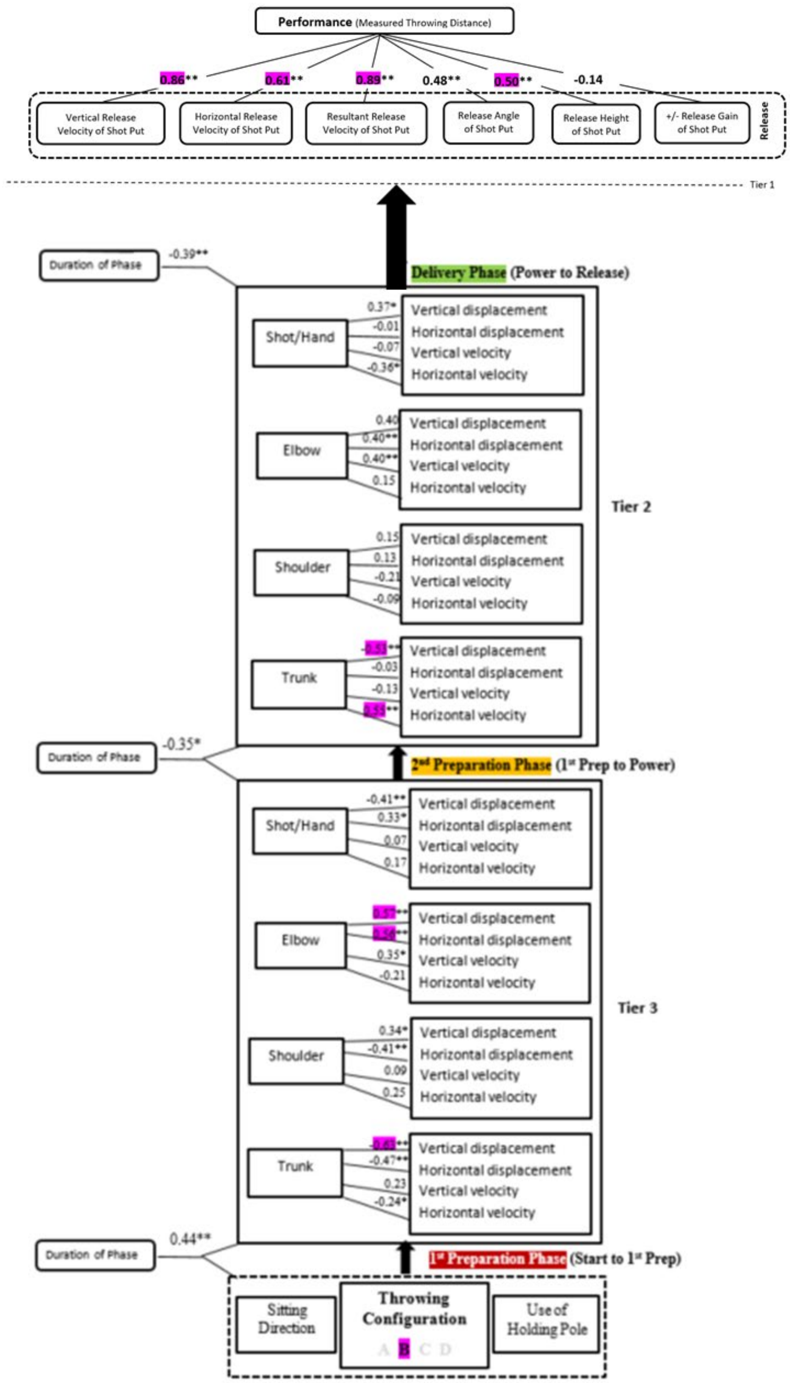


Figure 7 2: A visual representation showing Tiers 3, 2 and 1 of the deterministic model for seating Configuration B, showing the Pearson's correlation r values and level of significance (two-tailed) between key variables and performance for **all** throws. Only strong correlations (>0.50) are highlighted in pink. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

Seating Configuration C

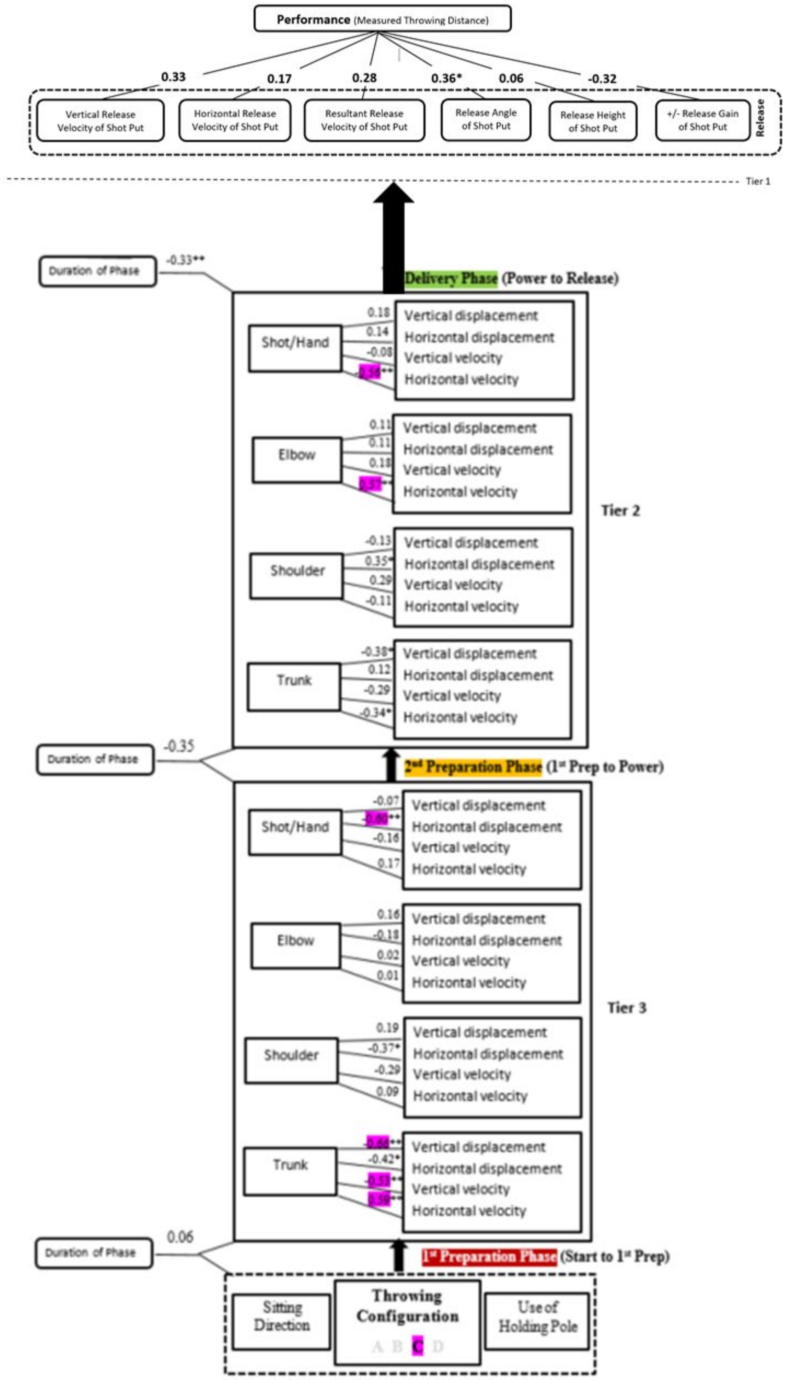


Figure 7 3: A visual representation showing Tiers 3, 2 and 1 of the deterministic model for seating Configuration C, showing the Pearson's correlation r values and level of significance (two-tailed) between key variables and performance for **all** throws. Only strong correlations (>0.50) are highlighted in pink. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

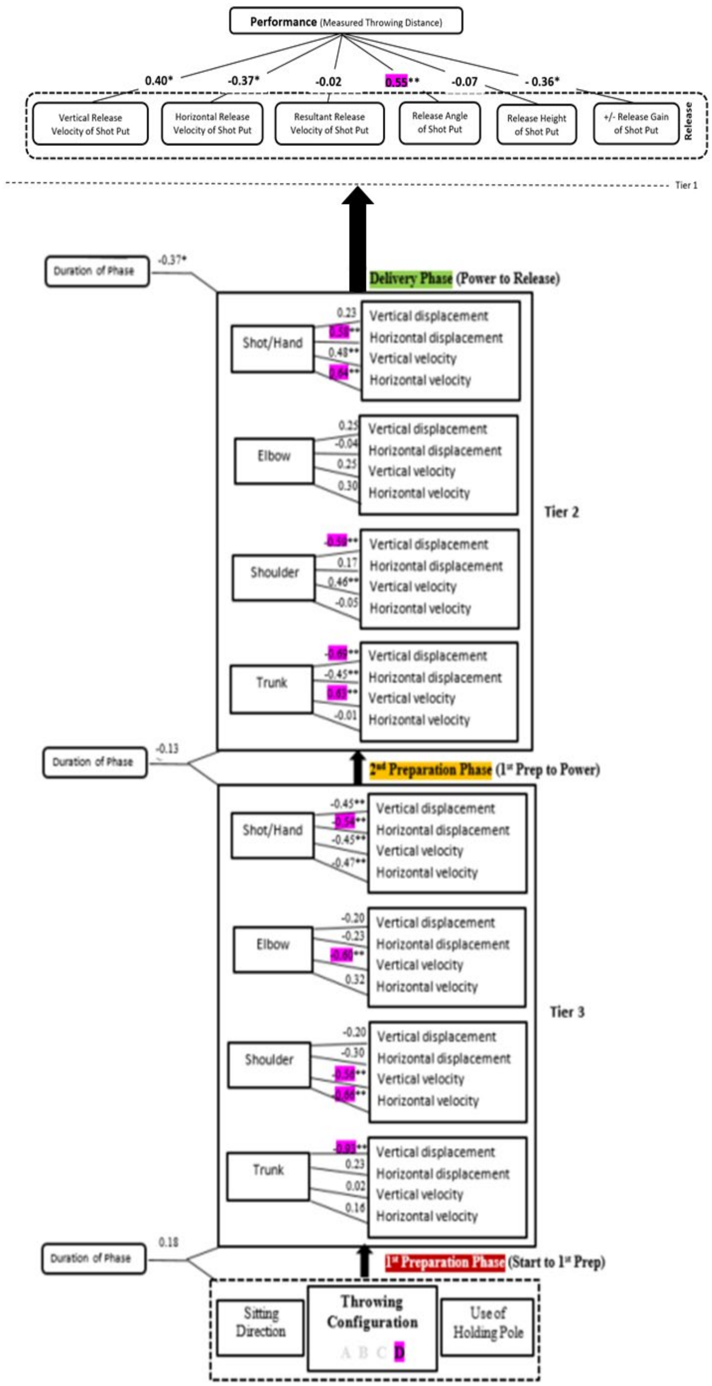


Figure 7 4: A visual representation showing Tiers 3, 2 and 1 of the deterministic model for seating Configuration D, showing the Pearson's correlation r values and level of significance (two-tailed) between key variables and performance for **all** throws. Only strong correlations (>0.50) are highlighted in pink. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

7.4 Key limitations

This work presented the typical limitations of a prospective observation study focusing on the performance analysis of elite para athletes. These included:

- Experimental settings: performing maximally with reflective markers on the joints, whilst throwing from a throwing frame and seating configurations that are unusual.
- Off event performance: since the variables would be correlated to performance, the participants were asked to throw maximally. Despite the testing environment being aligned as closely to competition, earlier research has shown that elite seated shot-putters performed on average 15 ±9% less than their personal best during in-lab data collection (Chow, Woen-Silk and Crawford 2000). However, one participant did achieve a personal best whilst throwing from an unusual seating configuration and throwing frame.
- Case-mix: the study was a sub-analysis as it relied on convenient sample size and focused on limited classifications. Although the sample size represented 24% of the seated throws population in the related classifications considered at a world class level, accuracy of results would be further increased with a larger number. Additionally, a larger cohort of participants across more functional classes would further increase the insight of how seating configuration might influence performance, for all seated shot-putters.

Furthermore, the overall design of the thesis presented additional limitations including:

- The world class athletes could only be accessed on one day, so all trials had to be completed just on that day. This meant that athletes were throwing 24 throws with maximal effort in close succession, and while they were given rest time in between each of the six throws, this may have impacted on their ability to throw maximally on each occasion, due to associated fatigue.
- They had all just finished competing at the World Championships, which may have had a related fatigue element. These fatigue factors may have had an influence on reliability of results due to some of the throws not being as maximal as required.
- Some athletes were not confident throwing from the seating configuration without a holding pole. This was due to their usual throwing configuration being with a holding

pole, and due to their trunk dysfunction. Consequently, the number of trials was lower for seating Configurations C and D.

- A systematic review of literature was not conducted.

7.5 Future directions

Future directions could expand on the themes developed in this thesis. This would involve more longitudinal studies which would replicate the process but generate more data by including:

- A larger cohort of participants across more classifications.
- Creating case studies for each of the elite participants to optimise feedback to the athlete and their coach.
- A validation of the error differences between manual and electronic (EDM) measurement in the shot-put.
- A full analysis of differing parabolic flight durations to assess error of measured to calculated performance.
- A kinematic analysis of key joints involving angular aspects of the full throwing movement, such as joint angle and angular velocity and how these inform the technical aspects prior to release.
- Holding pole positioning in relation to the non-throwing hip and its relationship to performance.
- How the point of kinetic chain change (closed to open) coincides or relates to the bracing and subsequent deceleration of the non-throwing side.
- Correlating the performance zone to performance.
- In-competition analysis.

Additionally, more cross-sectional studies would add further context to the understanding of the technical aspects of seated shot-put. These could include:

- EMG studies of trunk and elbow involvement from the power to release positions, as mentioned in Chapter 6.
- Data from inverse dynamics to inform the forces being applied by the athlete to the throwing frame.

- Developing a more intricate hand model to be able to evaluate wrist and hand as separate segments.
- Angular kinematic data to inform the movement patterns.
- Exploring if seating pressure would better inform the use of strapping, not only to secure the athlete to the throwing frame, but to influence functional movement also.

The results from this thesis can educate research design for future longitudinal and cross-sectional studies described above.

7.6 Conclusion

This thesis attempted to improve the understanding of the interaction of the seated shot-putter to their throwing frame. Critical new insights making contextual links between movement theory and practice for seated shot-putters and their coaches were provided. Recommendations that presented the key variables that correlated strongly with performance were developed. This was for both the release and the upper body linear kinematic variables. The underlying philosophy of this thesis was to provide information that was relevant and usable to coaches and other practitioners.

It is suggested that seating configurations that use a holding pole, may lead to better performance. This is despite the increased task-led constraints' that have been imposed by the 2014 WPA rule change and explained in Table 2 2. Additionally, using a holding pole could be considered as adding another task-led constraint, as it prevents the shot-putter from utilising their non-throwing arm in a bracing action, like standing shot-put. However, it is possible that seated shot-putters in the classes with lower levels of spinal dysfunction, such as F55, may require a holding pole, particularly in the early stages of their training. Those athletes that currently do not use a holding pole may take some time to alter their technique to be able to accommodate the pole.

The higher functioning spinal classifications in seated shot-put (F55 and F56) were the focus. The results showed that using a holding pole was a good predictor of performance for athletes in these classifications. This evidence could provide some argument to para athletics rule design whereby athletes up to and including F56 have to use a holding pole. Athletes in the higher classification, F57, where there is no spinal dysfunction may not need to use a holding pole.

This research was an initial milestone providing information that coaches have been requesting for a very long time. It will inform coaches' technical decision making with regards to seating configuration. It is anticipated that more in-depth longitudinal studies will be conducted at a later date, to include a greater number of athletes across different classifications. Additionally, evidenced based cross-sectional studies based on angular kinematic data would further enrich the context of the coaching guidance.

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Appendices

Appendix A – Ethics Information

A.1 Ethics Approval

Middlesex University London

London Sport Institute REC

The Burroughs
Hendon
London NW4 4BT

Main Switchboard: 0208 411 5000

07/11/2016

APPLICATION NUMBER: 0557

Dear Alison O'Riordan

Re your application title: Biomechanics of seated shot put

Supervisor: Andrew Greenhalgh

Thank you for submitting your application. I can confirm that your application has been given approval from the date of this letter by the London Sport Institute REC.

Please ensure that you contact the ethics committee if any changes are made to the research project which could affect your ethics approval.

The committee would be pleased to receive a copy of the summary of your research study when completed.

Please quote the application number in any correspondence.

Good luck with your research.

Yours sincerely

Chair Dr Rhonda Cohen

London Sport Institute REC

A.2 Participant Information Sheet

Middlesex University
London Sport Institute

Study Title

The interaction between throwing technique of seated shot-putters and their throwing frame.

Invitation to participate

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

The purpose of the study

This study is being undertaken as part of research (PhD) for Alison O'Riordan.

The purpose of this study is to:

- Increase the understanding of the interaction between the seated athlete and his/her throwing frame.
- Provide general principles and guidelines for the construction of a throwing frame
- Improve coach education by enhancing and updating current curriculum in the area of seated throwing
- Improve the performance of elite seated throwers.

The research team requests your assistance in collecting cutting-edge data including kinematic (3-Dimensional Motion Analysis System), and sitting pressure data recorded simultaneously.

Why have you been chosen?

You have been chosen to participate in this study as you have been identified as an emerging or elite seated thrower.

Do you have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

A decision to withdraw at any time, or a decision not to take part, will in no way impact upon your current or future relationship with the London Sports Institute or their researchers.

What will happen to me if I take part?

The sessions will involve throwing the shot-put a maximum of twenty four (24) times from a custom made throwing frame. You will need to wear tight fitting (or minimal) clothing.

Fluorescent anatomical (sticky) markers (approx. 30 in total) will be placed on your joint centres. Kinematic data will be collected using a Qualisys 3D motion analysis system.

- The kinematic data will be analysed to provide biomechanical information on the contribution of each body segment during the shot-put throwing action. It is also expected that the favourable body position will be determined by a combination of relevant kinematic parameters, and the indicators of maximal performance (identified at point of release of the shot-put using the high-speed video footage).

A seating pressure mat will be placed on top of the seated area of the throwing frame. You will be asked to throw whilst sitting on the pressure mat.

- A sitting pressure mat will determine the profile of sitting pressure generated during the throwing action, with a view to informing seating material and strapping systems.

What do I have to do?

Your participation will involve coming to Lee Valley Athletics Centre on Saturday 22 July 2017 for a duration of approximately two hours. You will be asked to undertake your own warm-up routine. You will then be asked to throw maximally from the throwing frame up to a maximum of 24 times from 4 seating configurations.

What are the possible benefits of taking part?

It is hoped that participating in the study will help you, by improving your performance. However, this cannot be guaranteed. The information obtained from this study may help us to better inform athletes and coaches of favourable sitting positions and throwing frame design.

Will my taking part in this study be kept confidential?

All information that is collected about you during the course of the research will be kept strictly confidential. Any information about you which is used will have your name and address removed so that you cannot be recognised from it. All data will be stored, analysed and reported in compliance with the Data Protection Legislation of the United Kingdom.

What will happen to the results of the research study?

This research will be published as part of a PhD dissertation, due to be submitted in October 2018. A copy of the results can be obtained from the Researcher, Alison O'Riordan (see below for contact information). You will not be identified in any report/publication.

Who has reviewed the study?

The Middlesex University London Sports Institute Research Ethics Committee has reviewed this study.

Contact for further information

Research Team Contacts	
Alison O'Riordan, PhD Candidate, London Sports Institute, Middlesex University	Dr. Stuart Miller, Senior Lecturer, London Sports Institute, Middlesex University
07729 336 216	0208 411 5292
oriordan.alison@gmail.com	s.miller@mdx.ac.uk

You, the participant will be given a copy of the information sheet and a signed consent form to keep.
Thank you for taking part in this study.

A.3 Participant Consent Form

Middlesex University
London Sport Institute

Participant Identification Number:

PARTICIPANT CONSENT FORM

Title of Project: **The interaction between throwing technique of seated shot-putters and their throwing frame.**

Name of Researcher: **Alison O'Riordan**

1. I confirm that I have read and understand the information sheet dated ....……………..…for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.
3. I agree that this form that bears my name and signature may be seen by a designated auditor.
4. I agree that my non-identifiable research data may be stored in National Archives and be used anonymously by others for future research. I am assured that the confidentiality of my data will be upheld through the removal of any personal identifiers.
5. I agree to take part in the above study.

Name of participant	Date	Signature
______________________________	___________	______________________________
Name of person taking consent (if different from researcher)	Date	Signature
______________________________	___________	______________________________
Researcher	Date	Signature
______________________________	___________	______________________________

1 copy for participant; 1 copy for researcher.

A.4 Venue Risk Assessment

Lee Valley Park
Open spaces and sporting places

RISK ASSESSMENT FORM
Issue 1

Centre: LV Athletics Centre	Date: 1.1.16	Carried out by Mick Bond

Risk Assessment: Indoor Throws Area

List significant hazards	List groups of people who are at risk from the significant hazards identified	List existing control measures or note where the information may be found List risks which are not adequately controlled on the risk reduction plan
Risk: Floor Surface		
Injuries from slipping/tripping	Athletes Officials	• Athletes should wear adequate footwear. • Track maintenance & inspection regime • Area kept clean. Circles checked for damage on a monthly basis. • Any change of height is clearly identified. • Runways and track are swept to remove dirt, grit •
Risk: Injuries from thrown implements		
Injuries from Indoor Javelins, Shots, discus or hammers	Athletes Officials	• Under 16's not allowed in Centre unless supervised • Staff patrol for incorrect use of area – Athletes expected to follow UKA guidance on throwing events • Netting in place and checked on a monthly basis • Implements checked on a monthly basis • Competition supervised by qualified officials • Implements stored away when not in use

Lee Valley Park
Open spaces and sporting places

RISK ASSESSMENT FORM
Issue 1

Centre: LV Athletics Centre	Date: 1.1.16	Carried out by Mick Bond

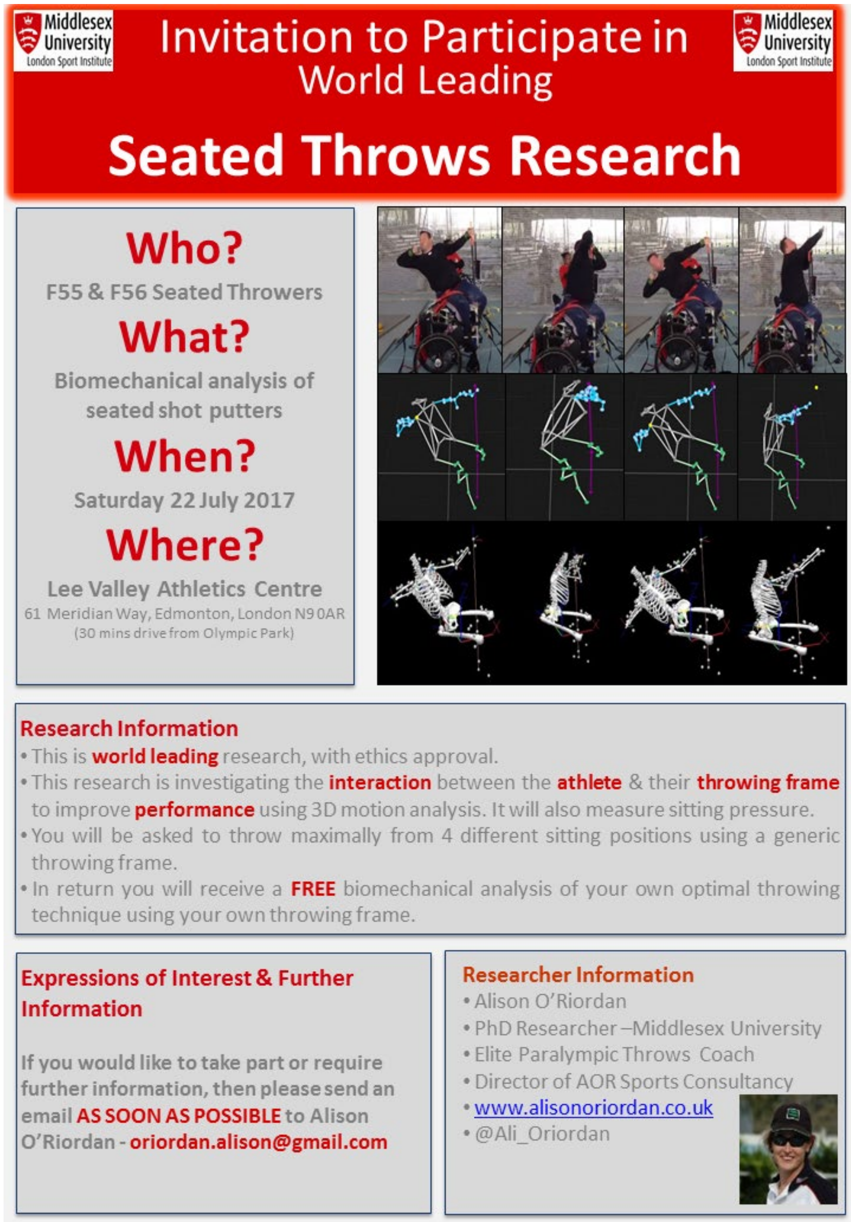
Risk Assessment: Indoor Throws Area

Risk: Setting Up Of Equipment		
Injury from incorrect handling/lifting.	Staff	• Staff Training in manual handling • Staff carry out manual handling safe practice when setting up shot and Discus circles.
Risk: Personal Injury		
Personal Injury	Athletes Officials	• First aider on site at all times

Appendix B – Research Preparation/Outputs

B.1 Invite to Participant

Invitation sent via the National Paralympic Committees (NPCs) of all athletes ranked in the World top ten. It was also promoted by The International Paralympic Committee (IPC).



B.2 Athlete Information Sheet

Athlete ID:

Testing Order:

Middlesex University
London Sport Institute

Biomechanics of Seated Throwing

Personal Information

Name: ……………………………………………………………………………………………

Contact email:……………………………………………………………………………………

Date of Birth:……………………………………………………………………………………

Body Mass (kg): …………………………………………………………………………………

Sitting Height (m): ………………………………………………………………………………

Throwing Hand (please circle): Right Left

Usual throwing configuration (please circle): Front On with Pole

Diagonal On with Pole Front On without Pole Diagonal On without Pole

Other (please state): ……………………………………………………………………………

Classification: ……………………………………………………………………………………

Year of Injury: ……………………………………………………………………………………

Diagnosis e.g. Complete lesion at T8…………………………………………………………..

B.3 Randomised Throwing Sequence

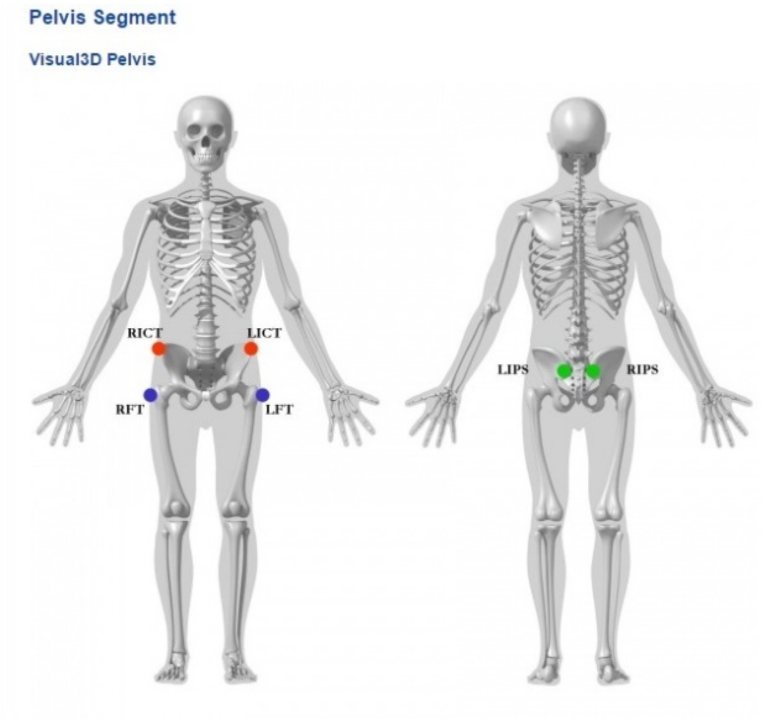
THROWING ORDER

1	2	3	4	5
A	B	C	D	E
A	B	D	C	E
B	A	C	D	E
B	A	D	C	E
C	D	B	A	E
C	D	A	B	E
D	C	B	A	E
D	C	A	B	E

A	Front On + Pole
B	Side On + Pole
C	Front On + NO Pole
D	Side On + NO Pole
E	Own Frame

B.4 Reflective marker positioning for Visual 3D

Pelvis Segment



V3D Pelvis

RFT, LFT = Femur greater Trochanter

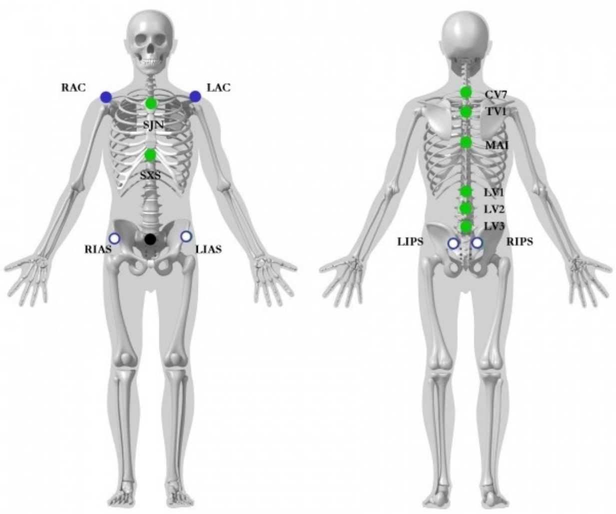
RICT, LICT = Ilium Crest Tubercle (Iliac Crest)

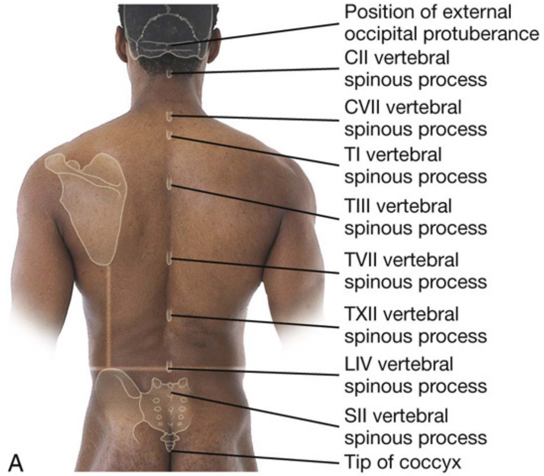
RIPS, LIPS = Ilium Posterior Superior (Posterior Superior Iliac Spine)

Markers	Anatomical marker placement
Shoulder ref. frame	
Left shoulder	Left acromion process
Right shoulder	Right acromion process
Lower thorax ref. frame	
Sternum	Xiphoid process, distal end of the sternum
T10 vertebrae	Tenth thoracic spinous process (T10)
L1 vertebrae	First lumbar spinous process (L1)
Pelvis ref. frame	
Left anterior pelvis	Left anterior superior illiac spine (LASIS)
Right anterior pelvis	Right anterior superior illiac spine (RASIS)
Left posterior pelvis	Left posterior superior illiac spine (LPSIS)
Right posterior pelvis	Right posterior superior illiac spine (RPSIS)

Thorax Segment

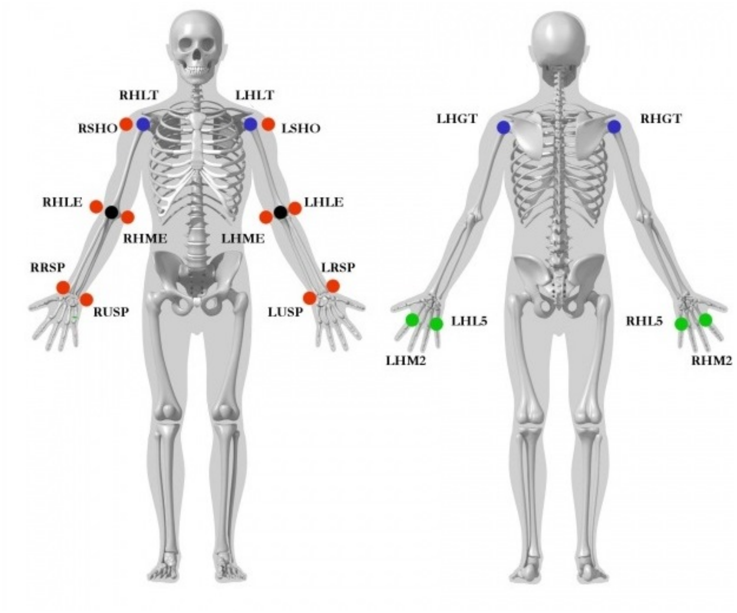
This marker set is consistent with the ISB recommendations.





Thorax Segment
C7
T10
L1
Sternum
R and L Shoulder
R and L Greater Trochanter
R and L ASIS and PSIS

Upper Limbs



Upper Limb Segments

Shoulders

RHLT, LHLT= Humerus Lesser Tubercle;

RHGT, LHGT= Humerus Greater Tubercle

RSHO, LSHO

Elbow =

RHLE, LHLE= Lateral Epicondyle of Humerus

RHME, LHME= Medial Epicondyle of Humerus

Wrist =

RRSP, LSRP=Radius-Styloid Process

Hand

5th metatarsal (RandL) – dorsal

2nd metatarsal (RandL) – dorsal

These hand markers to be attached with tape around hand

Cluster markers on upper and lower arms

Upper Limbs

In this model, there are 3 markers surrounding the head of the humerus. The origin of the upper arm is the projection of the lateral shoulder marker onto an axis passing through the anterior and posterior shoulder markers.

RHLT, LHLT= Humerus Lesser Tubercle

RHGT, LHGT= Humerus Greater Tubercle

RSHO, LSHO= Shoulders

RHLE, LHLE= Lateral Epicondyle of Humerus

RHME, LHME= Medial Epicondyle of Humerus

RHNT, LHNT= Navicular Tubercle

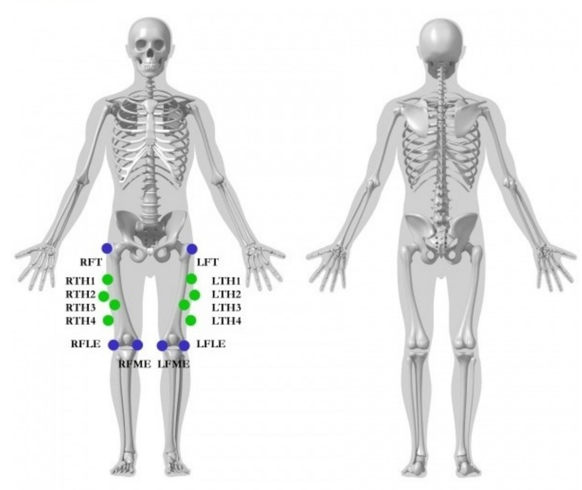
RRSP, LRSP=Radius-Styloid Process

RUSP, LUSP=Ulna-Styloid Process

RHL, LHL, RHM, LHM= Lateral and Medial Head of Metacarpal

Thigh Segment

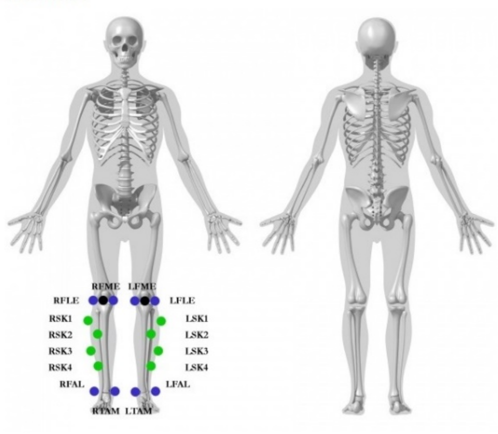
Thigh Model 1



Thigh Model 1
RFT, LFT = Femur greater Trochanter
RFLE, LFLE=Femur Lateral Epicondyle
RFME, LFME=Femur Medial Epicondyle
A cluster plate will be used in place of R and LTH1-4 (green markers here)

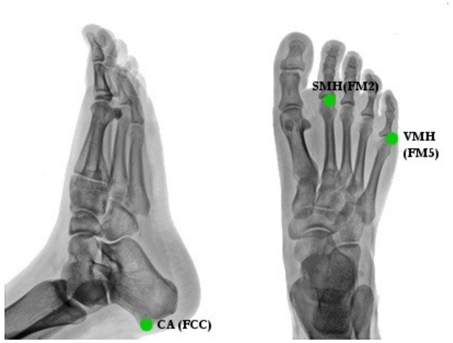
Shank Segment

Shank Model 2



Shank Model 2
FLE, LFLE = Femur Lateral Epicondyle
RFME, LFME = Femur Medial Epicondyle
RFAL, LFAL = Fibula Apex of Lateral Malleolus
RTAM, LTAM= Tibia Apex of Medial Malleolus
A cluster plate will be used in place of R and LSK1-4 (green markers here)

Foot Model



Foot Model
CA (FCC) = Posterior Surface of Calcaneus
SMH(FM2) = Head of 2nd Metatarsus
VMH(FM5) = Head of 5th Metatarsus
To be placed on shoe

Head Model

Head Model
RAC, LAC= Acromion
A head band with markers will be used for this

B.5 Example of initial report sent to athletes

KINEMATIC ANALYSIS OF SEATED SHOT-PUT

LEE VALLEY ATHLETICS CENTRE, LONDON

22 JULY 2017

REPORT FOR XXX ATHLETE

XXX

Presented by

Alison O'Riordan[1,2], Laurent Frossard[3,4,5] and Stuart Miller[6]

[1]London Sports Institute, Middlesex University, UK;

[2]AOR Sports Consultancy

[3]Queensland University of Technology, Australia
[4]University of the Sunshine Coast, Australia
[5]YourResearchProject, Australia
[6]Centre for Sports and Exercise Medicine, Queen Mary University of London, UK.

Last up-date: 8 April, 2021

This report has been compiled from 3D motion data collected from world class seated throwers as part of a research project entitled "The interaction between seated throwers and their throwing frame".

It is a biomechanical report intended for coach and athlete use. The data has been produced via Qualisys programme.

It contains the following:

- General information about the data collection and analysis
- General performance information
- A description of the seating configurations
- The parameters of the trajectory
- Determination and definitions of the events and phases of the shot-put throwing action
- Spatial, temporal and velocity variables of the shot-put throwing action.

General information about the data **collection and analysis**

Table 1: General information	
Assigned initials	JBJ
Age	45
Gender	Male
Body Mass (kg)	96
Height (m)	1.87
Class	F55
Dominant Side	Right
Sampling of acquisition (Hz)	250
Weight of Shot-put (kg)	4
Number of Seating Configurations	4
Total number of trials	24

Table 2: Performance Information

Seating Configuration	Front On with Holding Pole	Diagonal On with Holding Pole	Front On without Holding Pole	Diagonal On without Holding Pole
Trial 1 (m)	9.46	8.80	7.72	7.59
Trial 2 (m)	9.65	9.10	8.00	7.37
Trial 3 (m)	9.53	9.10	8.45	7.90
Trial 4 (m)	9.59	8.80	8.52	8.00
Trial 5 (m)	8.99	9.23	8.55	8.06
Trial 6 (m)	9.59	8.86	8.76	8.30
Mean (m)	9.47	8.98	8.25	7.87
SD	0.24	0.18	0.57	0.34

Max (m)	9.65	9.23	8.76	8.30

		Front On both knees facing forward	**Diagonal On** left knee facing forward, right knee facing diagonal to the side
With Holding Pole	**Power Position**		
	Release Position		
Without Holding Pole	**Power Position**		
	Release Position		

Figure 1: Seating Configurations (Power to Release positions)

Parameters determining the trajectory of the put

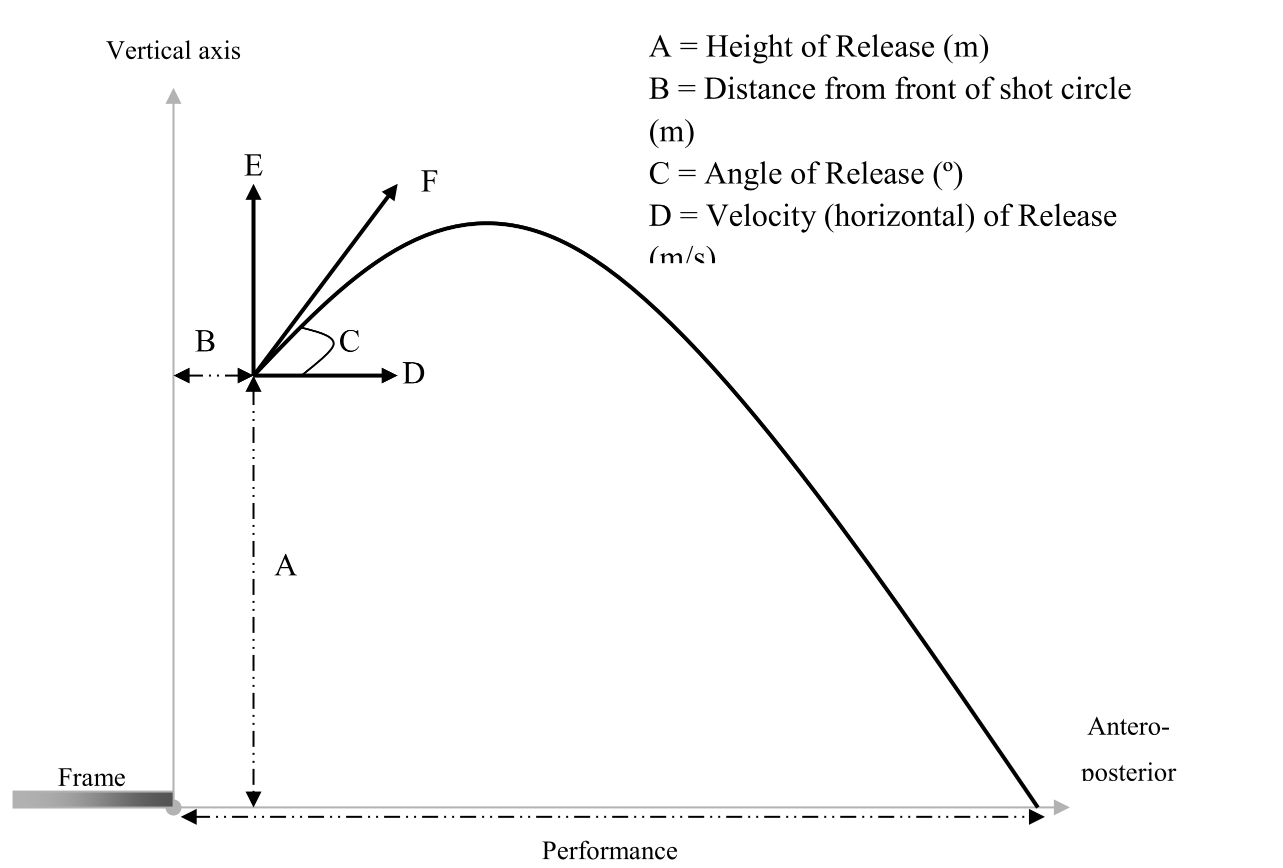


Figure 2: Definition of the parameters of the trajectory

Table 4: Parameters associated with the trajectory of the shot-put

		Front On with Holding Pole	Diagonal On with Holding Pole	Front On without Holding Pole	Diagonal On without Holding Pole
Shot-put Release Parameters (mean ±SD)					
Performance (m)		**9.47 ±0.24**	**8.98 ±0.18**	**8.25 ±0.57**	**7.87 ±0.34**
Height of Release (m)	A	1.24 ±0.03	1.25 ±0.03	1.19 ±0.05	1.28 ±0.31
Distance from front of shot-put circle (m)	B	0.14 ±0.08	0.28 ±0.05	0.26 ±0.15	0.07 ±0.09
Angle at Release (º)	C	54.02 ±5.8	41.6 ±6.29	36.2 ±9.84	57.75 ±9.51
Velocity (horizontal) of Release (ms^{-1})	D	6.61 ±0.27	6.67 ±0.43	6.63 ±0.28	5.39 ±0.32
Velocity (vertical) of Release (ms^{-1})	E	4.97 ±0.25	4.18 ±0.35	3.66 ±0.56	4.20 ±0.21
Velocity (norm) of release (ms^{-1})	F	8.27 ±0.25	7.88 ±0.31	7.60 ±0.17	6.84 ±0.14

Determination and definitions of the events and phases of the shot-put throwing action

Each throw was determined by a specific set of events and segmented into several phases. These events were defined as:

Event	Definition
Start	The stationary position at the start of the throwing action
1st Preparation position	The position where the athlete changes direction at the front of the throwing frame. Technically this is considered a movement to generate momentum.
Power position	The position where the athlete changes direction at the back of the throwing frame. Technically this is considered to be the position that the athlete is applying maximum force into the final phase prior to release.
Release	The point at which the shot-put leaves the throwing hand.

The phases were defined as:

Phase	Definition
Initial Position	The same position as the **Start** of the throwing action (as defined above)
1st Forward movement	The 1st forward movement of the athlete moving from the Start position to the front of the throwing frame into the **1st Preparation position** (as defined above)
Backward movement	The backward movement of the athlete moving from the front (**1st Preparation position)** to the back of the throwing frame into **Power positio**n (as defined above).
2nd Forward movement	The 2nd forward movement of the athlete moving from the back (**Power position)** to the front of the throwing frame into the **Release** position (as defined above).
Final Position	The same position as the **Release** of the throwing action (as defined above).

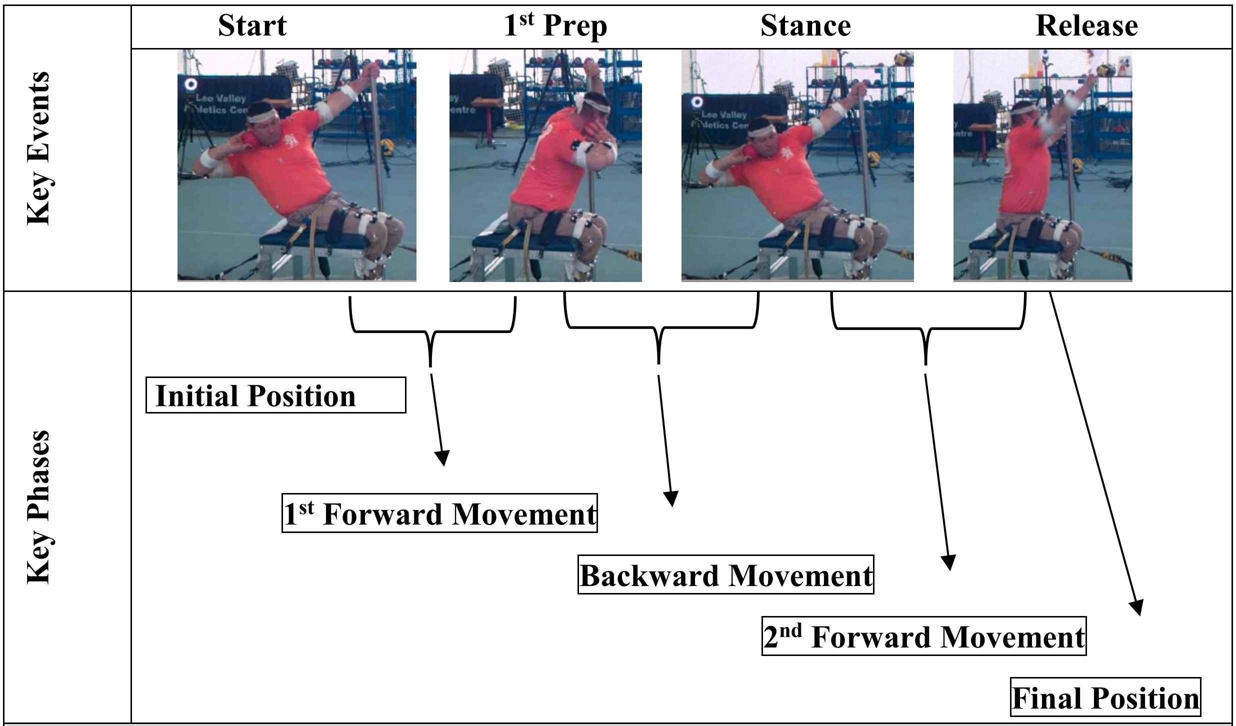


Figure 3: Definition of the key phases of the shot-put throw

Spatial, temporal and velocity variables of the shot-put

The variables that were used in the data analysis of this study were temporal, spatial and velocity based.

Spatial variables

The spatial variables refer to the distance (mean) the shot-put has travelled, in metres, between the key phases for the trial with the longest performance, for each seating configuration, and are presented in 3 ways:

- Shot-put movement in the throwing direction
- Shot-put movement in the vertical direction.

Table 5: Distance (mean) travelled by the shot-put between the key phases action for each seating configuration

	Front On with Holding Pole	Diagonal On with Holding Pole	Front On without Holding Pole	Diagonal On without Holding Pole
Performance (m)	**Trial 2** 9.65	**Trial 4** 9.23	**Trial 6** 8.76	**Trial 6** 8.30
Variable 1 Distance (mean) travelled in direction of throw	**(m)**	**(m)**	**(m)**	**(m)**
Total Distance travelled	2.11	2.20	1.47	1.33
1st Forward Movement	0.19	0.11	0.20	0.10
Backward Movement	0.89	0.89	0.37	0.44

2nd Forward Movement	1.03	1.20	0.90	0.79
Variable 2 Distance travelled in vertical direction	**(m)**	**(m)**	**(m)**	**(m)**
Total Distance travelled	1.29	1.49	1.14	1.26
1st Forward Movement	0.40	0.52	0.55	0.56
Backward Movement	0.13	0.15	0.05	0.11
2nd Forward Movement	0.76	0.82	0.54	0.59
Variable 3 Resultant Distance travelled	**(m)**	**(m)**	**(m)**	**(m)**
Total Distance travelled	2.62	2.88	2.01	2.00
1st Forward Movement	0.44	0.53	0.58	0.56
Backward Movement	0.90	0.90	0.37	0.45
2nd Forward Movement	1.28	1.45	1.05	0.98

Temporal variables

The temporal variables refer to the duration (mean), in seconds, between the key phases for each seating configuration, and are presented in 2 ways:

- In seconds
- As a percentage of the entire throw.

Table 6: Duration (mean) between the key phases of shot-put throw for each seating configuration

	Front On with Holding Pole	Diagonal On with Holding Pole	Front On without Holding Pole	Diagonal On without Holding Pole
Performance (m)	9.47 ±0.24	8.98 ±0.18	8.25 ±0.57	7.87 ±0.34
Variable 4 **Duration (mean)**	**(sec)**	**(sec)**	**(sec)**	**(sec)**
Total Duration	1.82	2.17	2.57	2.47
1st Forward Movement	0.84	1.11	0.95	1.03
Backward Movement	0.56	0.66	1.26	1.06
2nd Forward Movement	0.43	0.4	0.37	0.39
Variable 5 **Duration (mean)**	**(%Throw)**	**(%Throw)**	**(%Throw)**	**(%Throw)**
Total Duration	100	100	100	100
1st Forward Movement	46	51	37	42
Backward Movement	30	30	49	43
2nd Forward Movement	24	18	14	15

Velocity variables

The velocity variables, in m/s, refer to the velocity of the shot-put between the key events, for the trial with the longest performance, for each seating configuration, and are presented in 3 ways:

- Velocity of the shot-put in the throwing direction
- Velocity of the shot-put in the vertical direction
- Resultant velocity of the shot-put.

Table 7: Velocity of the shot-put at the key phases for each throwing configuration

	Front On with Holding Pole	Diagonal On with Holding Pole	Front On without Holding Pole	Diagonal On without Holding Pole
Performance (m)	**Trial 5** 9.42	**Trial 5** 9.52	**Trial 1** 8.02	**Trial 5** 8.25
Variable 6 Velocity of shot-put in direction of throw	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**
Initial Position	**-**	**-**	**-**	**-**
1st Forward Movement	**1.58**	**0.02**	**0.10**	**0.21**
Backward Movement	**1.45**	**0.21**	**0.24**	**0.23**
2nd Forward Movement	**7.00**	**6.79**	**6.49**	**6.37**
Variable 7 Velocity on vertical axis	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**
Initial Position	-	-	-	-
1st Forward Movement	0.52	0.07	0.004	0.03
Backward Movement	0.98	0.24	0.28	0.08
2nd Forward Movement	5.31	4.18	3.59	4.02
Variable 8 Resultant velocity	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**	**(ms^{-1})**
Initial Position	**-**	**-**	**-**	**-**
1st Forward Movement	1.66	0.07	0.10	0.21
Backward Movement	1.75	0.32	0.37	0.23
2nd Forward Movement	8.79	7.97	7.41	7.53

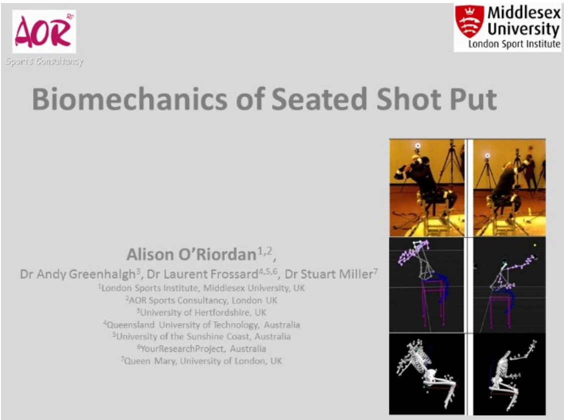
Acknowledgments

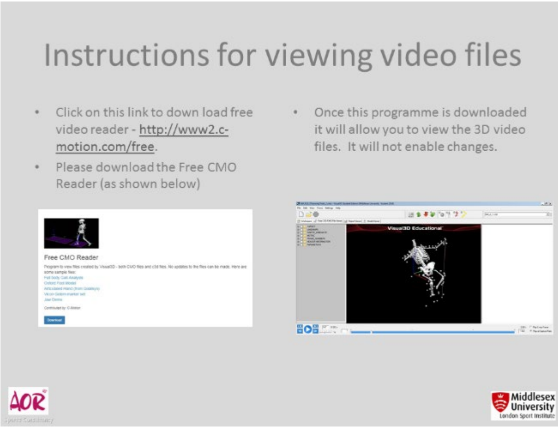
This study was funded by the London Sports Institute, Middlesex University, London, UK.
The authors wish to thank the following:

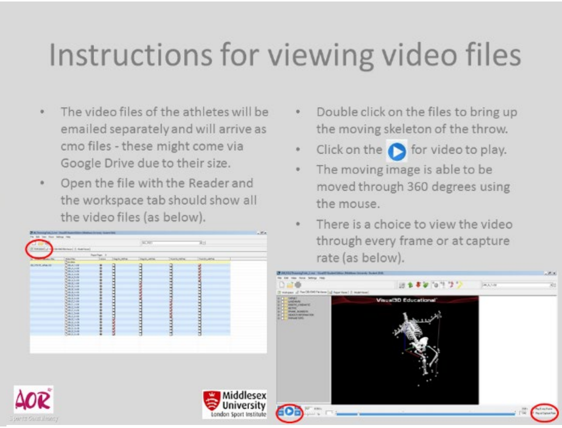
- Athletes from world leading NPCs for participating in the research
- Support staff from world leading NPCs for enabling their athletes to participate
- World Para Athletics for promoting the research
- Lee Valley Athletics Centre for providing the world class venue.

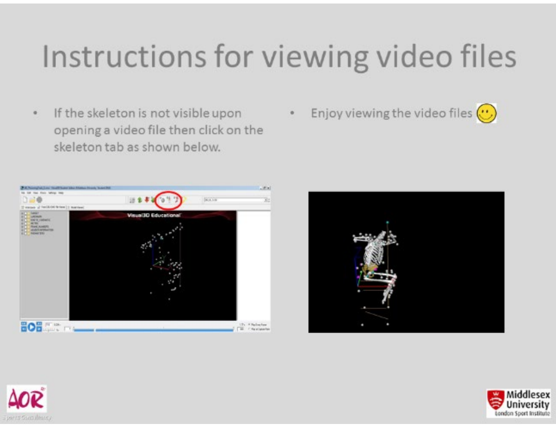
For enquiries or further information please contact:
Alison O'Riordan – oriordan.alison@gmail.com

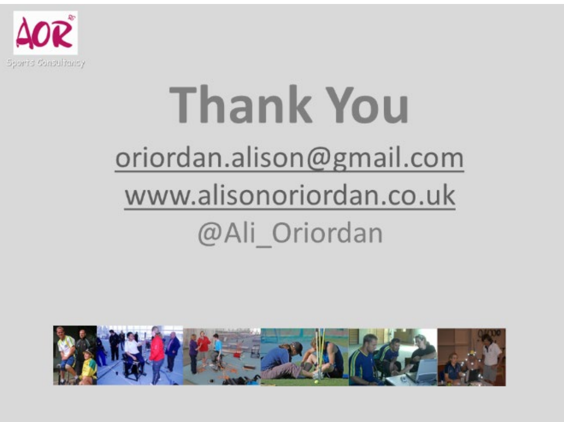
B.6 Access Instructions for participants and coaches







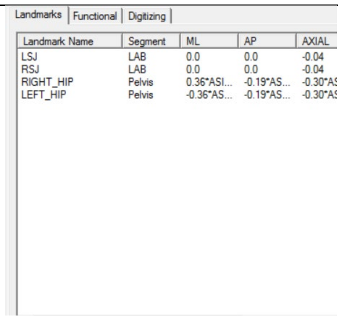




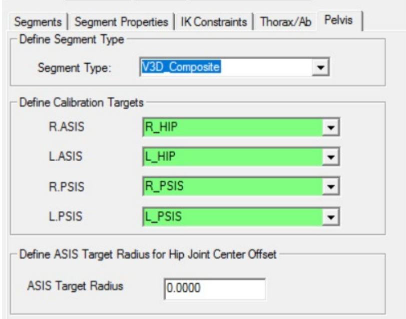
Appendix C - Chapter 4: Study 1

Table C 1: Details for joint creation including inverse kinematic constraints for right and left arms.

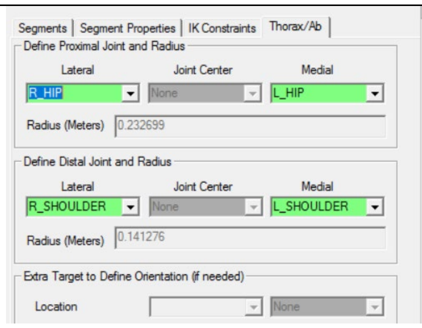
Landmarks



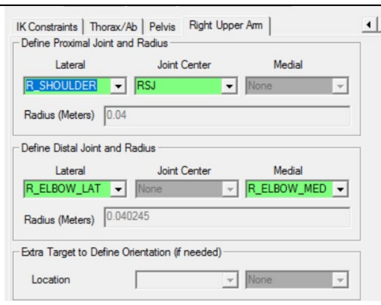
Pelvis

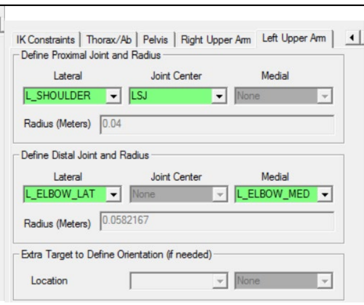


Thorax

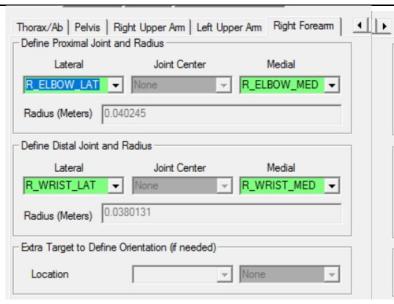


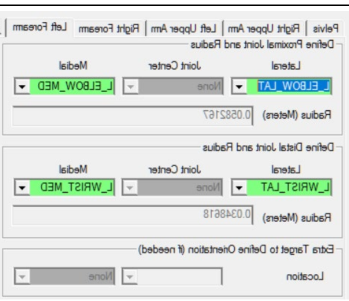
Upper Arms





Forearms

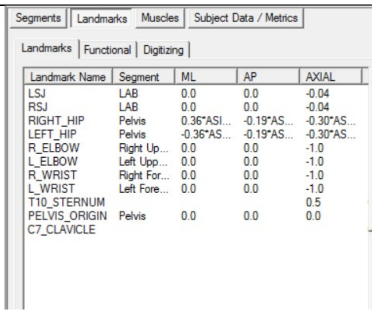




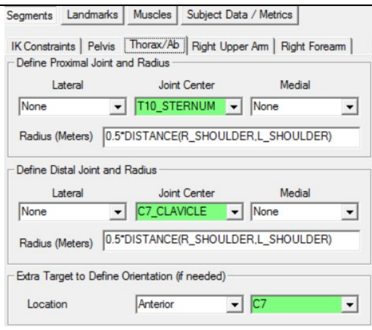
Appendix D – Chapter 5: Study 2

Table D 1: Details for joint creation including inverse kinematic constraints for right and left arms.

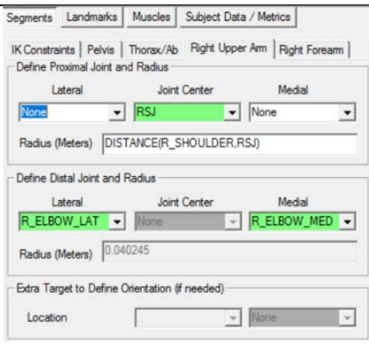
Landmarks

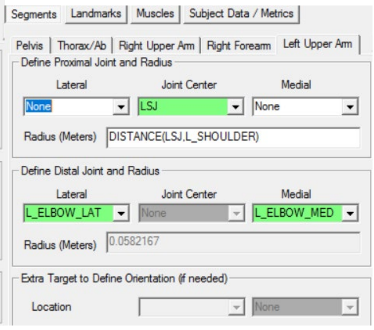


Thorax

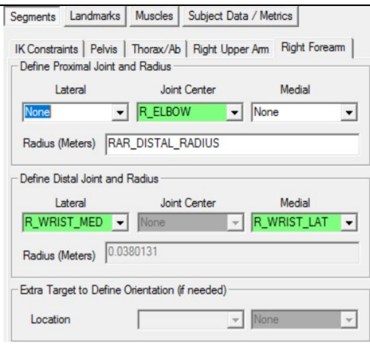


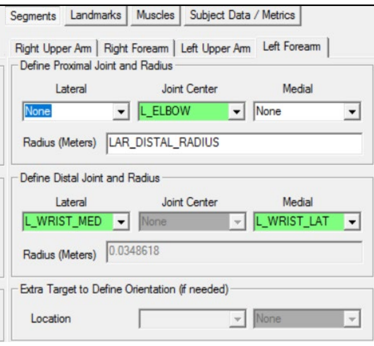
Upper Arms



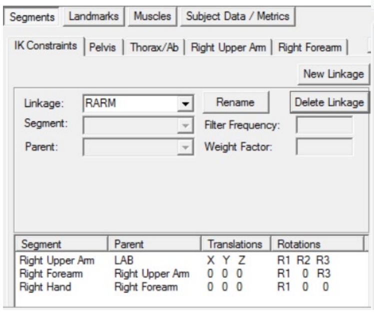


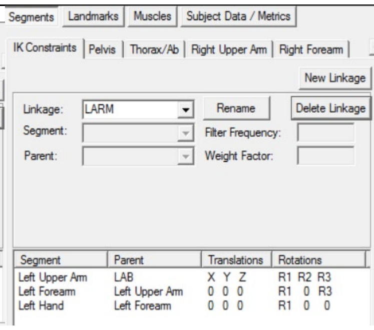
Forearms





IK Contraints





Study 2: Scatterplot diagrams of Shot-put release variables

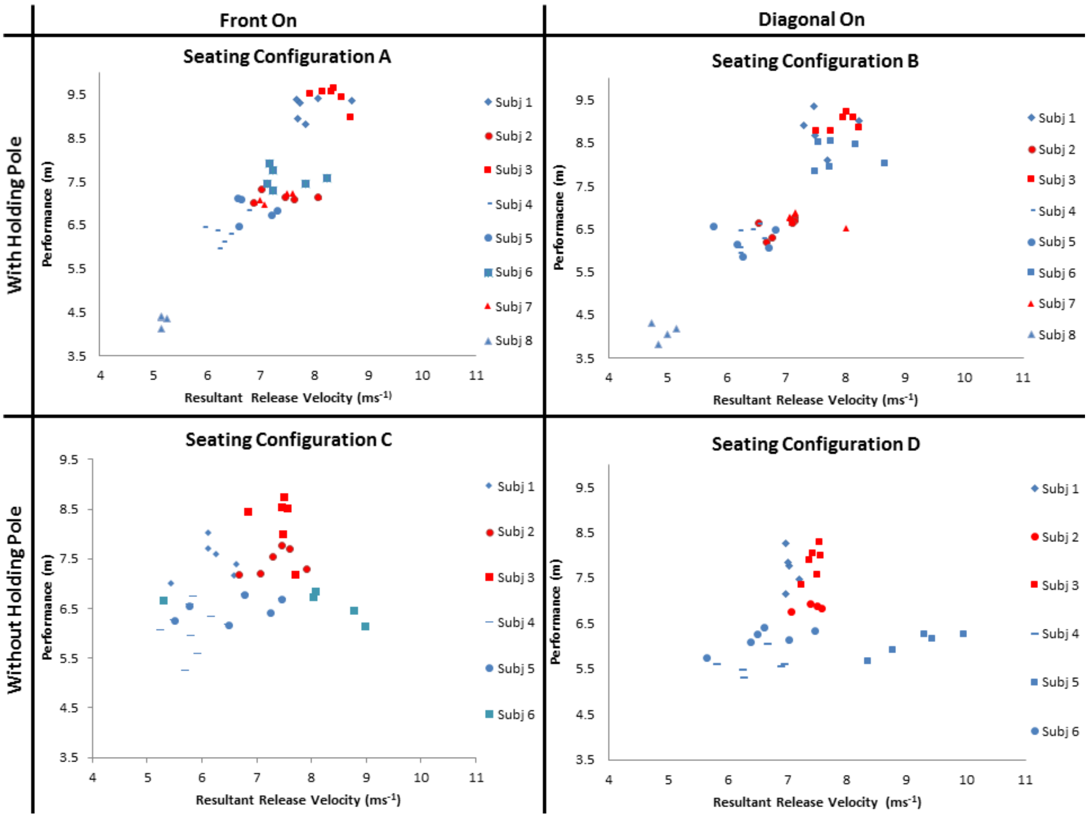


Figure D 1: Scatter plot of Resultant Release Velocity against Performance for each seating configuration.

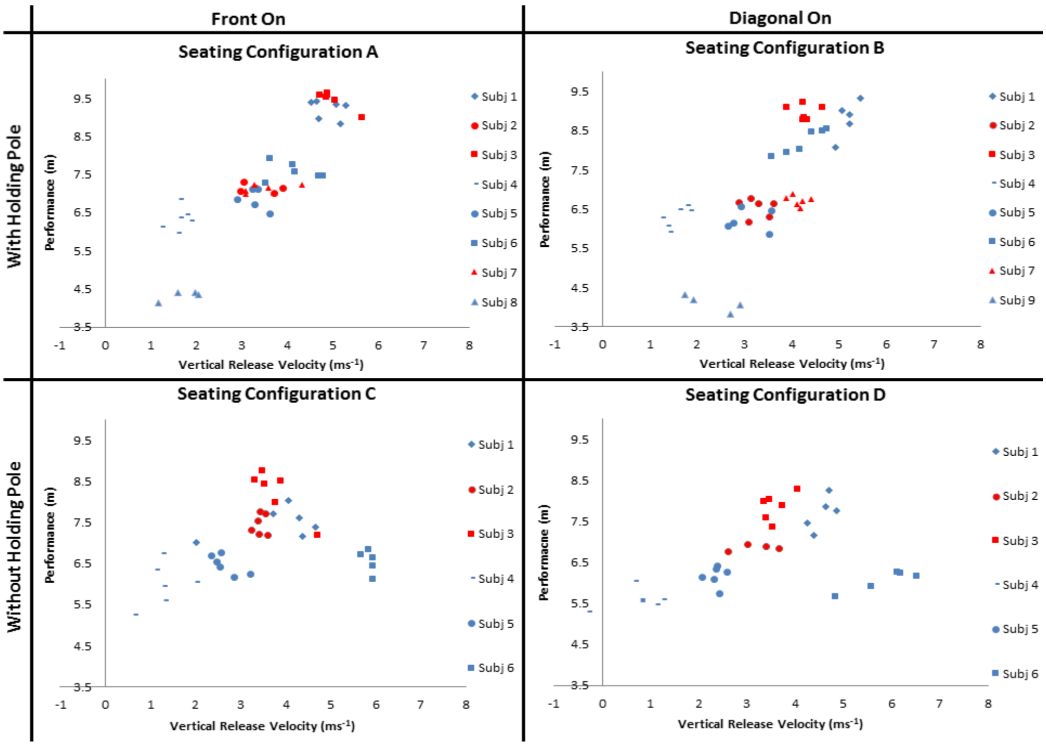


Figure D 2: Scatter plot of Vertical Release Velocity against Performance for each seating configuration.

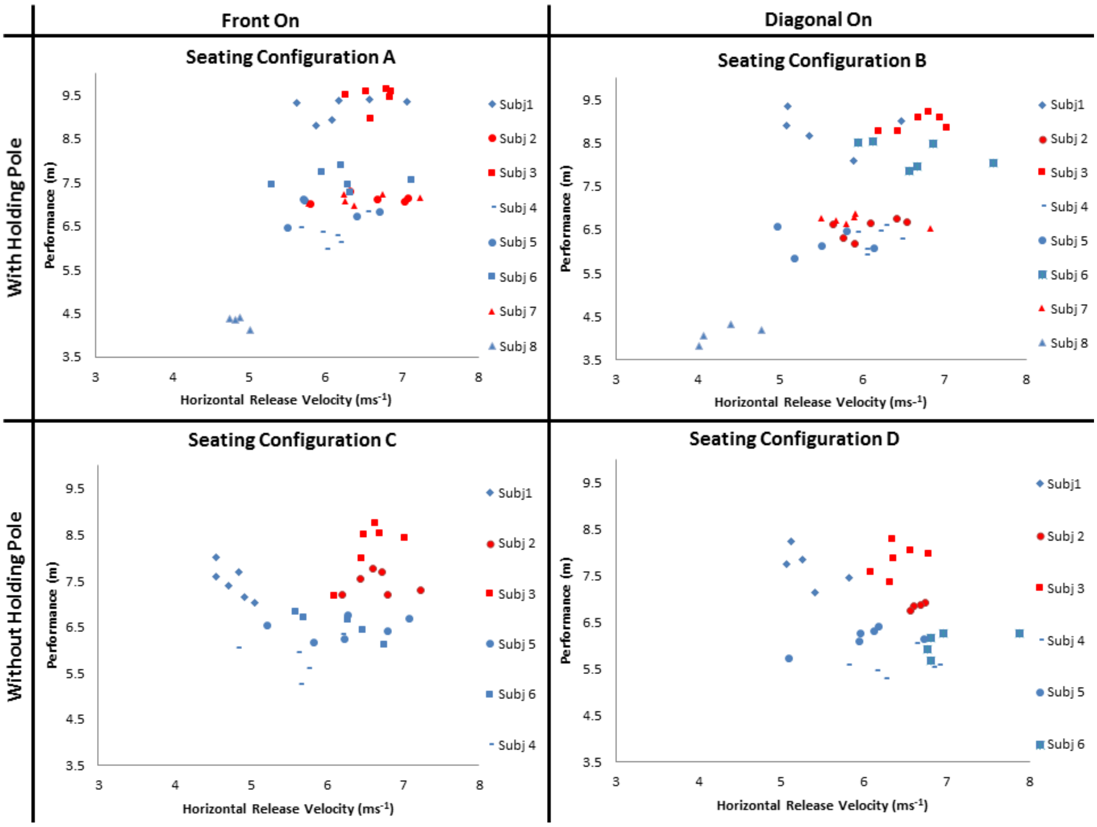


Figure D 3: Scatter plot of Horizontal Release Velocity against Performance for each seating configuration.

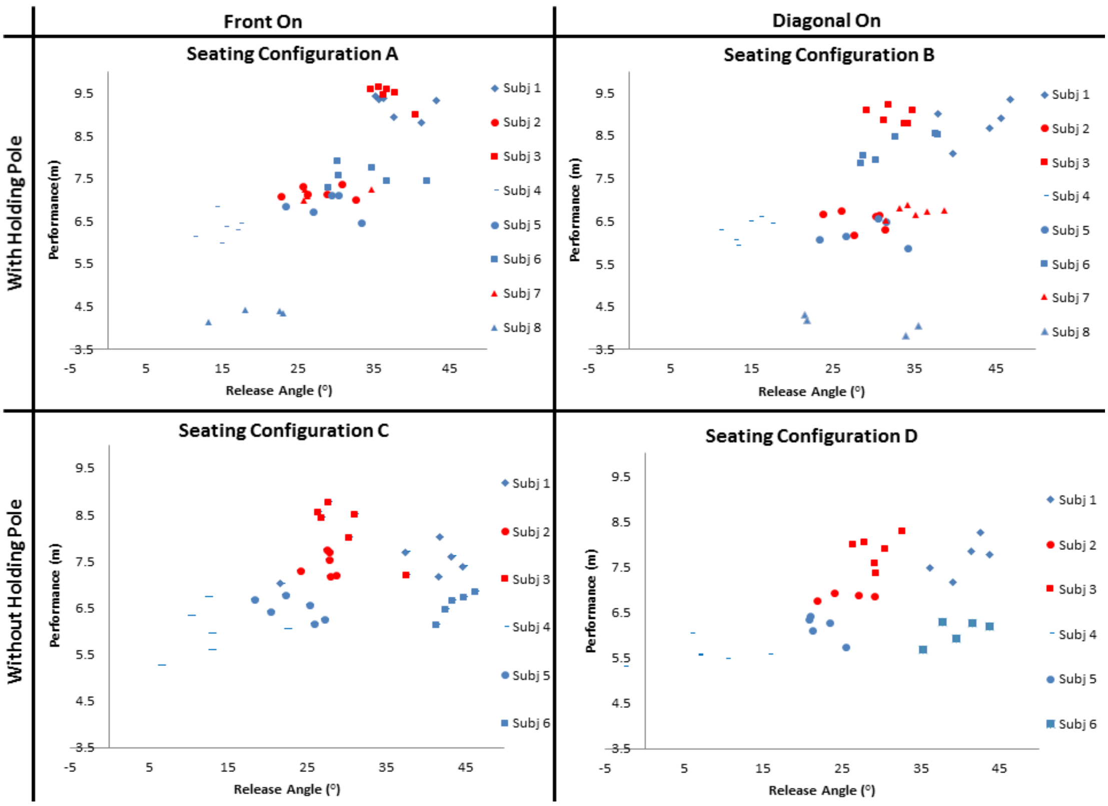


Figure D 4: Scatter plot of Release Angle against Performance for each seating configuration.

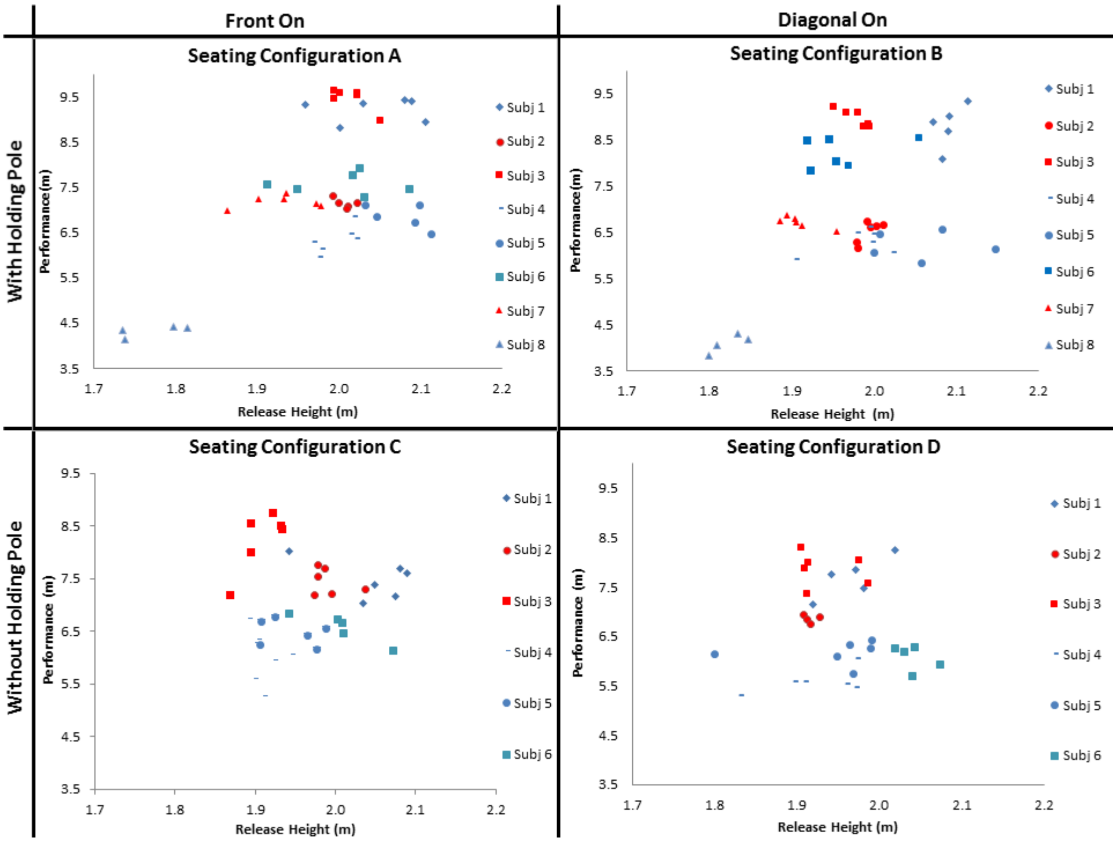


Figure D 5: Scatter plot of Release Height against Performance for each seating configuration.

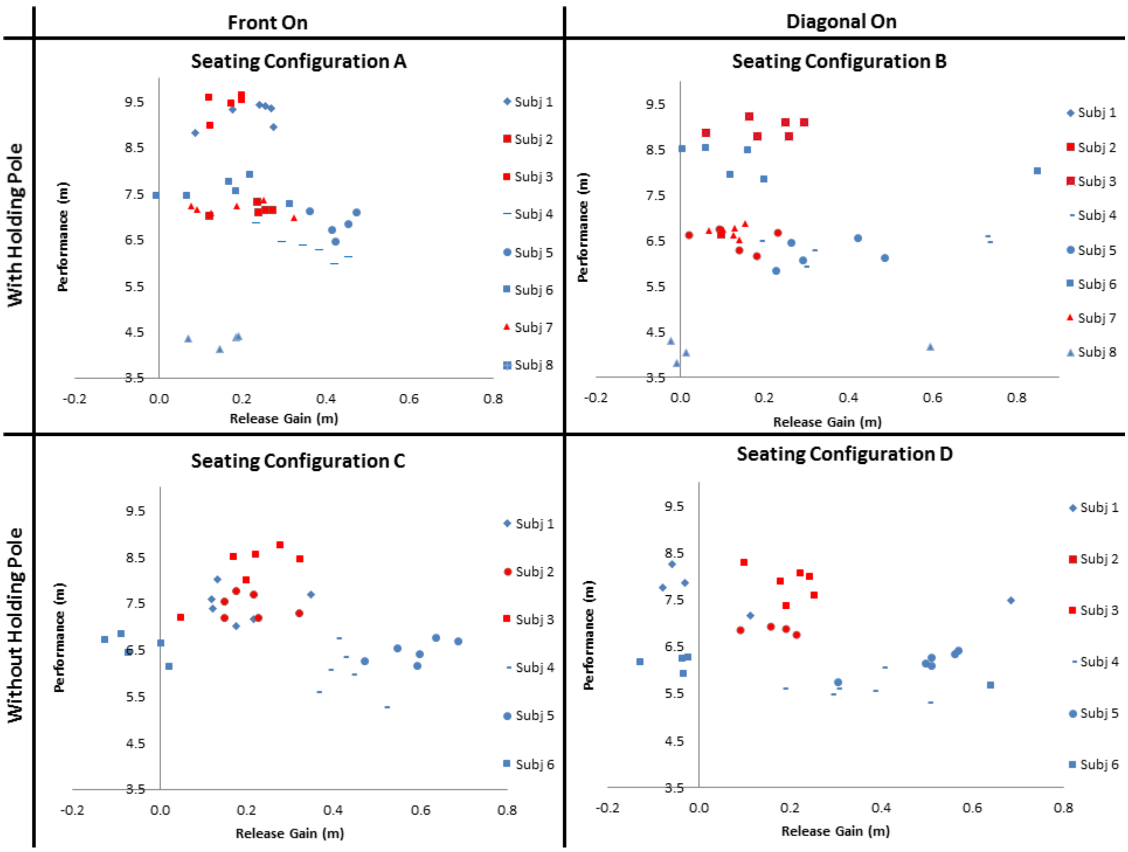


Figure D 6: Scatter plot of Release Gain against Performance for each seating configuration.

Study 2: Pearson's Correlation Analysis

Table D 2: Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put vertical velocity for all throws and the best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All throws	n = 44	n = 44	n = 35	n = 34
r	0.86	0.74	0.33	0.40
sig	0.01**	0.01**	0.05	0.05*
strength	Very Strong	Very Strong	Mod	Mod
Best throws	n = 8	n = 8	n = 6	n = 6
r	0.88	0.87	0.17	0.32
sig	0.01**	0.01**	0.75	0.54
strength	Very Strong	Very Strong	Low	Mod

Table D 3: Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put horizontal velocity for all throws and the best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All throws	n = 44	n = 44	n = 35	n = 34
r	0.57	0.61	0.17	-0.37
sig	0.01**	0.01**	0.33	0.05*
strength	Strong	Strong	Low	Mod
Best throws	n = 8	n = 8	n = 6	n = 6
r	0.78	0.52	-0.04	-0.64
sig	0.02*	0.19	0.95	0.17
strength	Very Strong	Strong	Neg	Strong

Table D 4:Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put resultant velocity for all throws and all best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole

All throws	n = 44	n = 44	n = 35	n = 34
r	0.88	0.89	0.28	0.02
sig	0.01**	0.01**	0.06	0.65
strength	Very Strong	Very Strong	Low	Neg
Best throws	n = 8	n = 8	n = 6	n = 6
r	0.92	0.90	0.03	-0.18
sig	0.01*	0.01**	0.96	0.74
strength	Almost Perfect	Almost Perfect	Neg	Low

Table D 5: Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put angle for all throws and the best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All throws	n = 44	n = 44	n = 35	n = 34
r	0.77	0.48	0.36	0.55
sig	0.01**	0.01**	0.05*	0.01**
strength	Very Strong	Mod	Mod	Strong
Best throws	n = 8	n = 8	n = 6	n = 6
r	0.80	0.73	0.26	0.64
sig	0.02*	0.04*	0.62	0.17
strength	Very Strong	Very Strong	Low	Strong

Table D 6: Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put height for all throws and the best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All throws	n = 44	n = 44	n = 35	n = 34
r	0.60	0.50	0.06	-0.07
sig	0.05*	0.01**	0.75	0.87
strength	Strong	Strong	Neg	Neg
Best throws	n = 8	n = 8	n = 6	n = 6
r	0.78	0.61	0.38	-0.31
sig	0.02*	0.10	0.62	0.56
strength	Very Strong	Strong	Low	Mod

Table D 7: Pearson's Correlation r value, significance (two-tailed) and association strength of performance against shot-put gain for all throws and all the best throws for seating Configurations A, B, C and D. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

	A Front On with pole	**B** Diagonal On with pole	**C** Front On without pole	**D** Diagonal On without pole
All throws	n = 44	n = 44	n = 35	n = 34
r	-0.17	-0.14	-0.32	-0.36
sig	0.29	0.36	0.06	0.05*
strength	Low	Low	Mod	Mod
Best throws	n = 8	n = 8	n = 6	n = 6
r	-0.11	-0.14	-0.27	-0.56
sig	0.80	0.75	0.61	0.15
strength	Low	Low	Low	Strong

Study 2: 2-way ANOVA Profile Plots

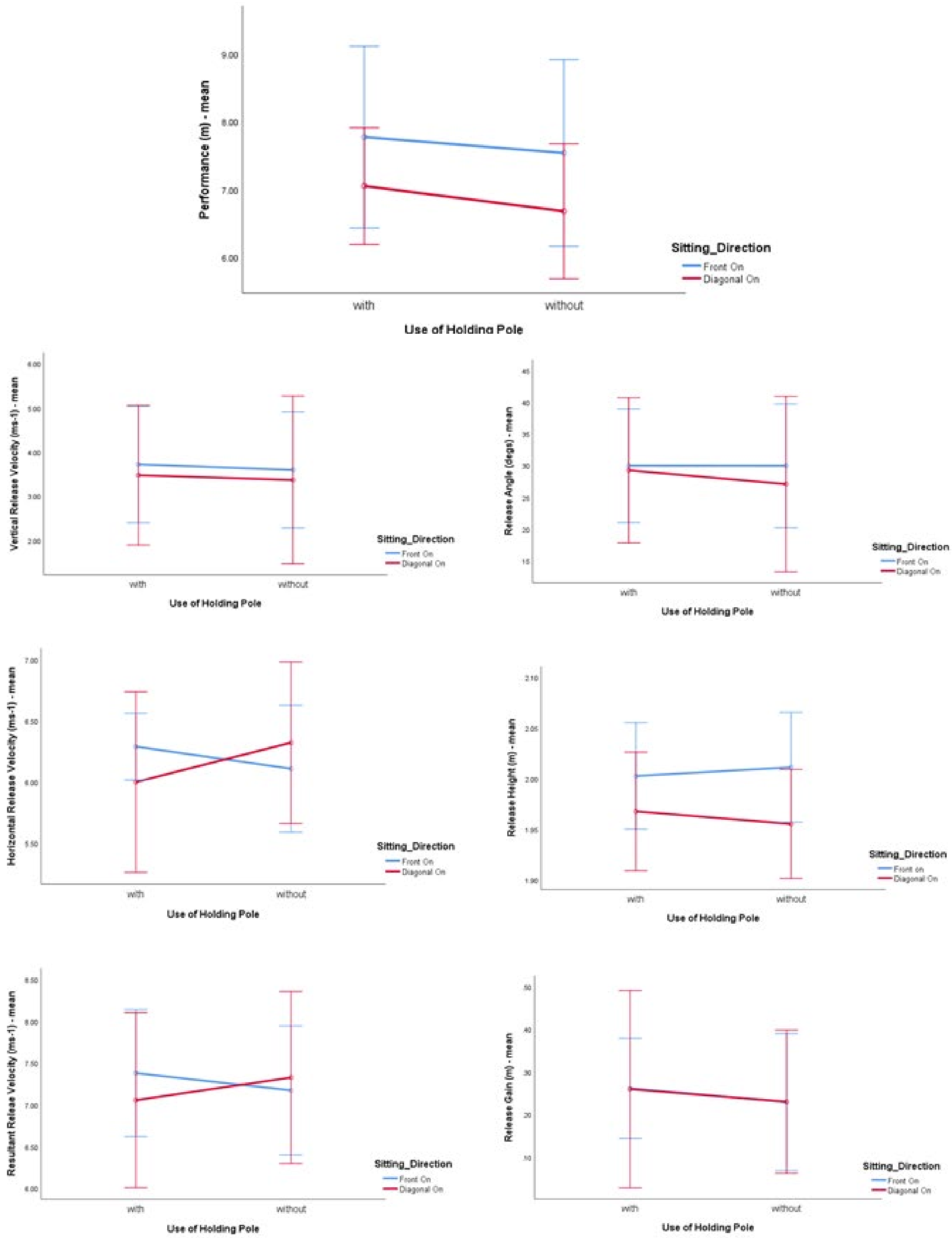


Figure D 7: Effect of seating configuration on mean shot-put release variables for all throws (95% Confidence level).

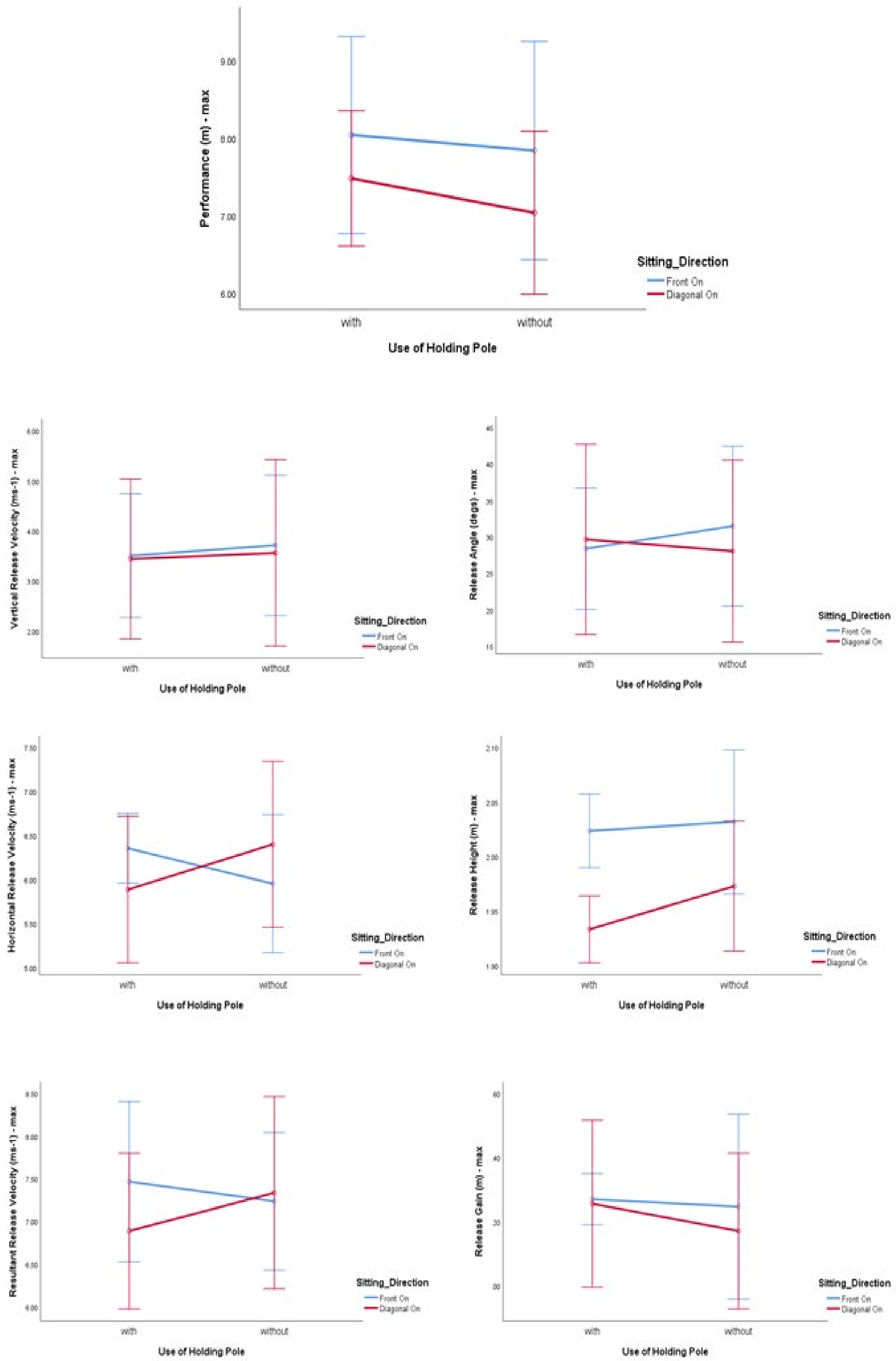


Figure D 8: Effect of seating configuration on performance and shot-put release variables for the best throws (95% Confidence level).

Table D 8: Stepwise (backward) regression of shot-put release variable against performance (all trials) for all seating configurations ($p<0.05$).

Seating Configuration		Unstandardised Coeffs B	Std Error	Standardised Coeffs Beta	t	Sig
A	Shot-put Vertical Velocity (ms^{-1})	2.00	0.27	1.70	7.38	0.01**
	Shot-put Angle (°)	-0.17	0.04	-0.98	-4.31	0.01**
	Shot-put Height (m)	4.37	1.06	0.26	4.12	0.01**
B	Shot-put Horizontal Velocity (ms^{-1})	-2.20	0.78	-1.15	-2.81	0.01**
	Shot-put Resultant Velocity (ms^{-1})	3.12	0.70	1.99	4.48	0.01**
	Shot-put Angle (°)	-0.01	0.05	-0.57	-2.19	0.05*
	Shot-put Height (m)	2.64	1.24	0.14	2.13	0.05*
C	Shot-put Vertical Velocity (ms^{-1})	-2.31	0.48	-3.85	-4.80	0.01**
	Shot-put Horizontal Velocity (ms^{-1})	1.57	0.30	1.41	5.27	0.01**
	Shot-put Angle (°)	0.34	0.07	4.34	5.27	0.01**
D	Shot-put Vertical Velocity (ms^{-1})	-2.16	0.58	-3.92	-3.75	0.01**
	Shot-put Horizontal Velocity (ms^{-1})	1.20	0.44	0.86	2.76	0.01**
	Shot-put Angle (°)	0.34	0.08	4.56	4.22	0.01**

Table D 9: Shot-put release variables: effect of position and pole, and their interaction, for Mean Values of all trials (df = 1; Error = 5).

	F	p
Mean Performance		
Sitting Direction	8.05	0.04*
Use of Holding Pole	7.06	0.05*
Interaction	0.25	0.64
Resultant Release Velocity		
Sitting Direction	0.07	0.80
Use of Holding Pole	0.03	0.86
Interaction	9.47	0.03*
Vertical Release Velocity		
Sitting Direction	0.35	0.58
Use of Holding Pole	0.65	0.46
Interaction	0.01	0.94
Horizontal Release Velocity		
Sitting Direction	0.04	0.85
Use of Holding Pole	0.17	0.70
Interaction	7.75	0.04*
Release Angle		
Sitting Direction	0.64	0.46
Use of Holding Pole	0.92	0.38
Interaction	2.43	0.18
Release Height		
Sitting Direction	3.17	0.14
Use of Holding Pole	0.02	0.90
Interaction	0.21	0.67
Release Gain		
Sitting Direction	0.00	0.99
Use of Holding Pole	0.66	0.46
Interaction	0.01	0.95

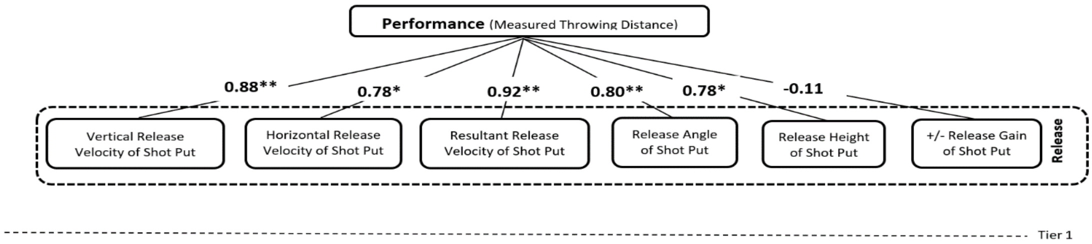


Figure D 9: Tier 1 of deterministic model for seating Configuration A showing the Pearson's correlation r values and significant (two-tailed) between release variables and performance for **best** throws. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

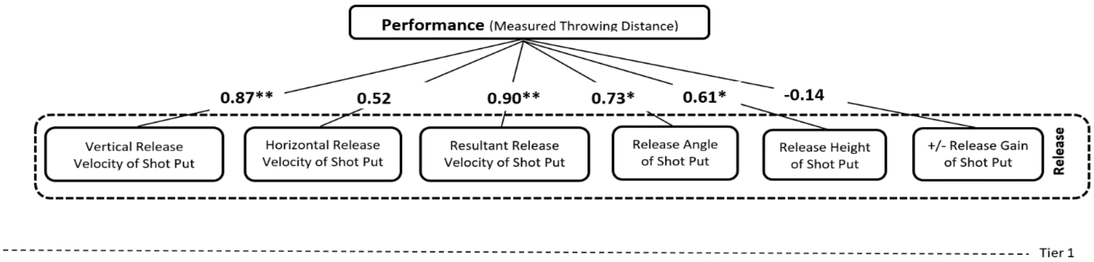


Figure D 10: Tier 1 of deterministic model for seating Configuration B showing the Pearson's correlation r values and significant (two-tailed) between release variables and performance for **best** throws. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

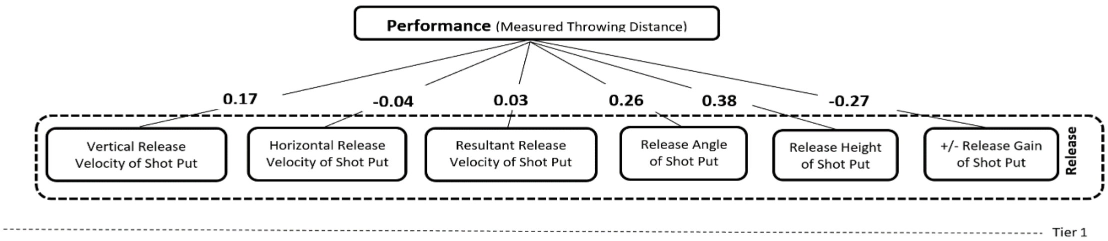


Figure D 11: Tier 1 of deterministic model for seating Configuration C showing the Pearson's correlation r values and significant (two-tailed) between key release variables and performance for **best** throws. Correlation is significant at the *0.05 level (2-tailed); or at the **0.01 level (2-tailed).

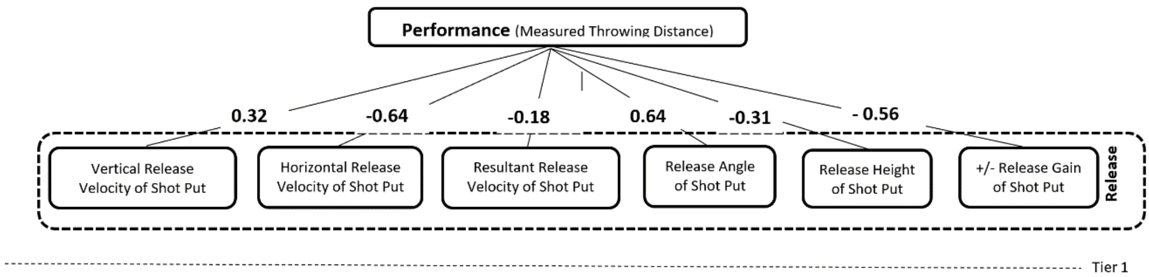


Figure D 12:Tier 1 of deterministic model for seating Configuration D showing the Pearson's correlation r values and significant (two-tailed) between key release variables and performance for **best** throws. Correlation is significant at the *0.05 level (2-tailed); or at the d**0.01 level (2-tailed)

Appendix E – Chapter 6: Study 3

Table E 1: Pearson's Correlation significance (two-tailed) and association strength of throwing phase duration, for all throws per seating Configuration. *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

	A Front On with pole (n = 44)	**B** Diagonal On with pole (n = 44)	**C** Front On without pole (n = 35)	**D** Diagonal On without pole (n = 34)
Delivery Phase				
r	-0.34	-0.39	-0.33	-0.37
sig	0.03*	0.01**	0.05*	0.03*
Strength	Mod	Mod	Mod	Mod
2nd Prep Phase				
r	-0.52	-0.36	0.33	-0.13
Sig	0.01**	0.02*	0.06	0.47
Strength	Strong	Mod	Mod	Low
1st Prep Phase				
r	0.47	0.44	0.06	0.18
Sig	0.01**	0.01**	0.72	0.30
Strength	Mod	Mod	Neg	Low

Table E 2: Pearson's Correlation significance (two-tailed) and association strength of shot-put vertical displacement, for all throws per seating Configuration. *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

	A Front On with pole (n = 44)	**B** Diagonal On with pole (n = 44)	**C** Front On without pole (n = 35)	**D** Diagonal On without pole (n = 34)
Tier 1 – Release				
Shot-put/Hand				
r	0.61	0.49	0.06	-0.10
sig	0.01**	0.01**	0.75	0.57
strength	Strong	Mod	Neg	Low
Elbow				
r	0.24	0.26	0.65	-0.15
sig	0.11	0.09	0.01**	0.39
strength	Low	Low	Strong	Low
Shoulder				
r	0.40	-0.08	0.12	-0.18
sig	0.01**	0.59	0.51	0.32
strength	Mod	Neg	Low	Low
Trunk				
r	-0.88	-0.68	-0.75	-0.82
sig	0.01**	0.01**	0.01**	0.01**

strength	Very Strong	Strong	Very Strong	Very Strong
Tier 2 – Power				
Shot-put/Hand				
r	0.03	0.37	0.18	0.23
sig	0.86	0.05*	0.31	0.19
strength	Neg	Mod	Low	Low
Elbow				
r	0.24	0.40	0.11	0.25
sig	0.12	0.01**	0.54	0.15
strength	Low	Mod	Low	Low
Shoulder				
r	0.17	0.15	-0.13	-0.59
sig	0.27	0.31	0.46	0.01**
strength	Low	Low	Low	Strong
Trunk				
r	-0.60	-0.53	-0.38	-0.69
sig	0.01**	0.01**	0.03*	0.01**
strength	Strong	Strong	Mod	Strong
Tier 3 – 1st Prep				
Shot-put/Hand				
r	-0.22	0.41	-0.07	-0.45
sig	0.16	0.01**	0.69	0.01**
strength	Low	Mod	Neg	Mod
Elbow				
r	0.33	0.57	-0.16	-0.20
sig	0.03*	0.01**	0.29	0.25
strength	Mod	Strong	Low	Low
Shoulder				
r	0.35	0.34	-0.19	-0.20
sig	0.02*	0.02*	0.30	0.24
strength	Mod	Mod	Low	Low
Trunk				
r	-0.71	-0.63	-0.66	-0.93
sig	0.01**	0.01**	0.01**	0.01**
strength	Very Strong	Strong	Strong	Almost Perfect

Table E 3: Pearson's Correlation significance (two-tailed) and association strength of horizontal displacement at Tiers 1, 2 and 3, for all throws per seating Configuration. *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

	A Front On with pole (n = 44)	B Diagonal On with pole (n = 44)	C Front On without pole (n = 35)	D Diagonal On without pole (n = 34)
Tier 1 - Release				
Shot-put/Hand				
r	-0.08	0.08	-0.30	-0.41
sig	0.62	0.60	0.08	0.02*
strength	Neg	Neg	Mod	Mod
Elbow				
r	-0.29	0.30	0.65	-0.06
sig	0.07	0.26	0.01**	0.72
strength	Low	Mod	Strong	Neg
Shoulder				
r	-0.25	0.11	0.17	0.08
sig	0.12	0.49	0.34	0.65
strength	Low	Low	Low	Neg
Trunk				
r	0.22	0.24	0.32	0.23
sig	0.15	0.11	0.06	0.91
strength	Low	Low	Mod	Low
Tier 2 – Power				
Shot-put/Hand				
r	-0.24	-0.01	0.14	0.58
sig	0.11	0.95	0.41	0.01**
strength	Low	Neg	Low	Strong
Elbow				
r	-0.34	0.40	0.11	-0.04
sig	0.03*	0.01**	0.54	0.84
strength	Mod	Mod	Low	Neg
Shoulder				
r	-0.01	0.13	0.35	0.17
sig	0.94	0.38	0.04*	0.32
strength	Neg	Low	Mod	Low
Trunk				
r	0.38	-0.03	0.12	-0.45
sig	0.02*	0.84	0.51	0.01**
strength	Mod	Neg	Low	Mod
Tier 3 – 1st Prep				
Shot-put/Hand				
r	0.19	0.33	-0.60	-0.54
sig	0.22	0.03*	0.01**	0.01**
strength	Low	Mod	Strong	Strong

Elbow				
r	-0.26	0.56	-0.18	-0.23
sig	0.09	0.01**	0.29	0.17
strength	Low	Strong	Low	Low
Shoulder				
r	-0.24	-0.41	-0.37	-0.30
sig	0.13	0.01**	0.03*	0.37
strength	Low	Mod	Mod	Mod
Trunk				
r	-0.18	-0.47	0.42	0.23
sig	0.25	0.01**	0.02*	0.19
strength	Low	Mod	Mod	Low

Table E 4: Pearson's Correlation significance (two-tailed) and association strength of vertical velocity at Tiers 1, 2 and 3, for all throws per seating Configuration. *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

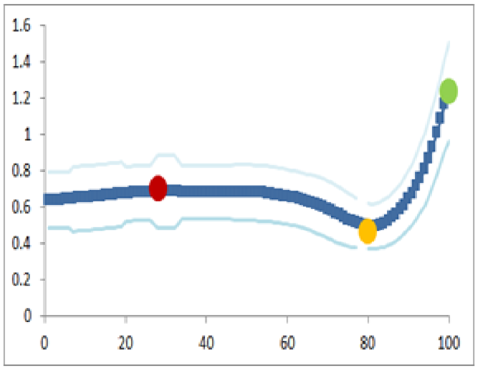
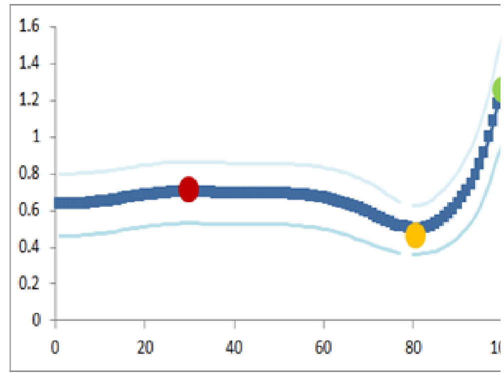
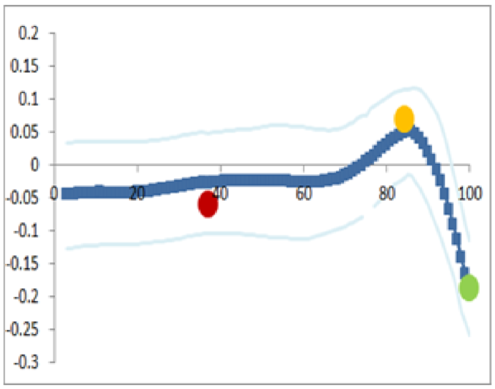
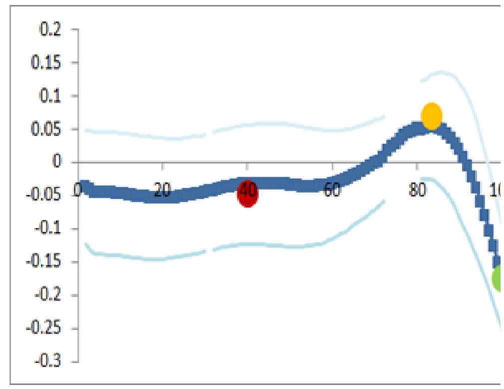
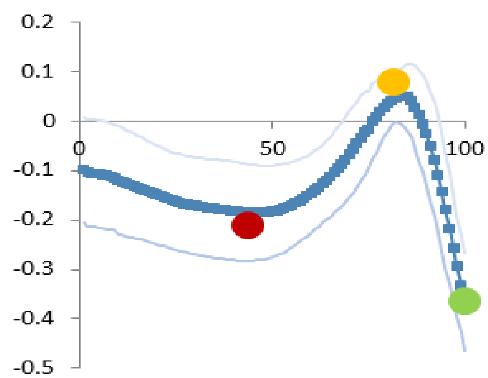
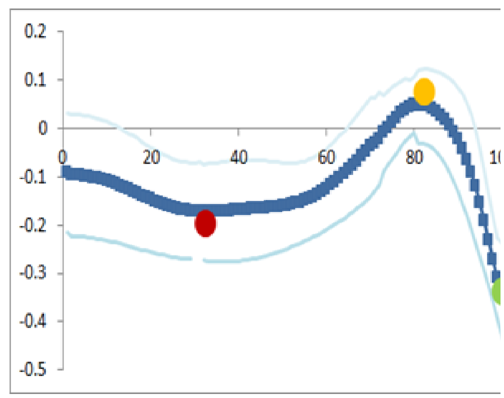
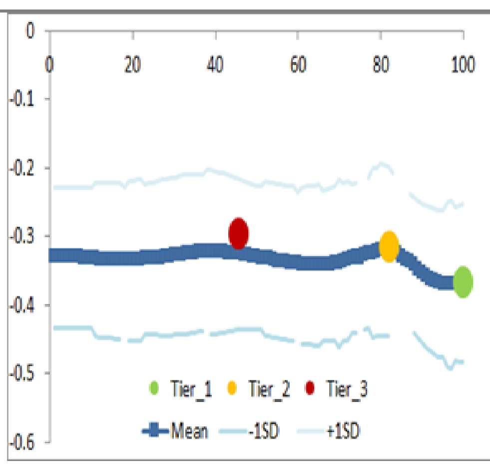
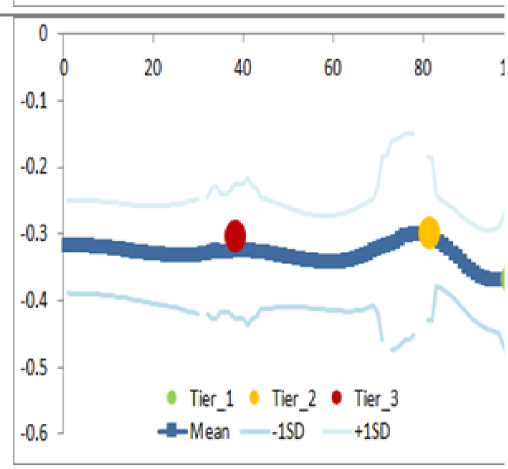
	A Front On with pole (n = 44)	**B** Diagonal On with pole (n = 44)	**C** Front On without pole (n = 35)	**D** Diagonal On without pole (n = 34)
Tier 1 – Release				
Shot-put/Hand				
r	0.86	0.74	0.33	0.40
sig	0.01**	0.01**	0.05*	0.05*
strength	Very Strong	Very Strong	Mod	Mod
Elbow				
r	-0.06	-0.42	-0.17	-0.15
sig	0.76	0.03*	0.33	0.37
strength	Neg	Mod	Low	Low
Shoulder				
r	0.49	0.72	0.27	-0.17
sig	0.01**	0.01**	0.33	0.33
strength	Mod	Very Strong	Low	Low
Trunk				
r	-0.16	-0.37	-0.43	-0.09
sig	0.36	0.05	0.01**	0.63
strength	Low	Mod	Mod	Neg
Tier 2 – Power				
Shot-put/Hand				
r	-0.47	-0.07	-0.08	0.48
sig	0.01**	0.64	0.63	0.01**
strength	Mod	Neg	Neg	Mod
Elbow				
r	-0.25	0.40	0.18	0.25
sig	0.12	0.01**	0.30	0.15

strength	Low	Neg	Mod	Low
Shoulder				
r	-0.59	-0.21	0.29	0.46
sig	0.01**	0.16	0.10	0.01**
strength	Strong	Low	Low	Mod
Trunk				
r	0.64	-0.13	-0.29	0.63
sig	0.01**	0.39	0.09	0.01**
strength	Strong	Low	Low	Strong
Tier 3 – 1st Prep				
Shot-put/Hand				
r	0.17	0.07	-0.16	0.45
sig	0.26	0.67	0.35	0.01**
strength	Low	Neg	Low	Mod
Elbow				
r	0.33	0.35	0.02	-0.60
sig	0.03*	0.02*	0.92	0.01**
strength	Mod	Mod	Neg	Strong
Shoulder				
r	0.19	0.09	-0.29	-0.50
sig	0.22	0.54	0.10	0.01**
strength	Low	Neg	Low	Strong
Trunk				
r	0.06	0.23	-0.53	0.02
sig	0.71	0.13	0.01**	0.91
strength	Neg	Low	Strong	Neg

Table E 5: Pearson's Correlation significance (two-tailed) and association strength of shot-put horizontal velocity at Tiers 1, 2 and 3, for all throws per seating Configuration. *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

	A Front On with pole (n = 44)	**B** Diagonal On with pole (n = 44)	**C** Front On without pole (n = 35)	**D** Diagonal On without pole (n = 34)
Tier 1 – Release				
Shot-put/Hand				
r	0.57	0.61	0.17	-0.37
sig	0.01**	0.01**	0.33	0.05*
strength	Strong	Strong	Low	Mod
Elbow				
r	0.28	0.06	0.52	0.41
sig	0.07	0.60	0.01**	0.02*
strength	Neg	Neg	Strong	Mod
Shoulder				
r	-0.16	-0.06	0.01	-0.66

sig	0.32	0.69	0.99	0.01**
strength	Low	Neg	Neg	Strong
Trunk				
r	-0.35	-0.46	0.57	0.16
sig	0.02*	0.01**	0.01**	0.35
strength	Mod	Mod	Strong	Low
Tier 2 – Power				
Shot-put/Hand				
r	-0.42	-0.36	-0.56	0.64
sig	0.01**	0.05*	0.01**	0.01**
strength	Mod	Mod	Strong	Strong
Elbow				
r	-0.05	0.15	0.57	0.30
sig	0.76	0.33	0.01**	0.08
strength	Neg	Low	Strong	Mod
Shoulder				
r	-0.30	-0.09	-0.11	-0.05
sig	0.05	0.58	0.54	0.79
strength	Mod	Neg	Low	Neg
Trunk				
r	0.54	0.55	-0.34	-0.01
sig	0.01**	0.01**	0.04*	0.99
strength	Strong	Strong	Mod	Neg
Tier 3 – 1st Prep				
Shot-put/Hand				
r	0.21	0.17	0.17	-0.47
sig	0.16	0.27	0.33	0.01**
strength	Low	Low	Low	Mod
Elbow				
r	-0.33	-0.21	0.01	0.32
sig	0.03*	0.17	0.97	0.06
strength	Mod	Low	Neg	Mod
Shoulder				
r	0.36	0.25	0.09	-0.66
sig	0.02*	0.10	0.62	0.01**
strength	Mod	Low	Neg	Strong
Trunk				
r	-0.35	-0.24	0.59	0.16
sig	0.02*	0.02*	0.01**	0.35
strength	Mod	Low	Strong	Low

	Configuration A Front On with holding pole	Configuration B Diagonal with holding pole
Shot put Vertical Displacement (m)		
Elbow Vertical Displacement (m)		
Shoulder Vertical Displacement (m)		
Trunk Vertical Displacement (m)		

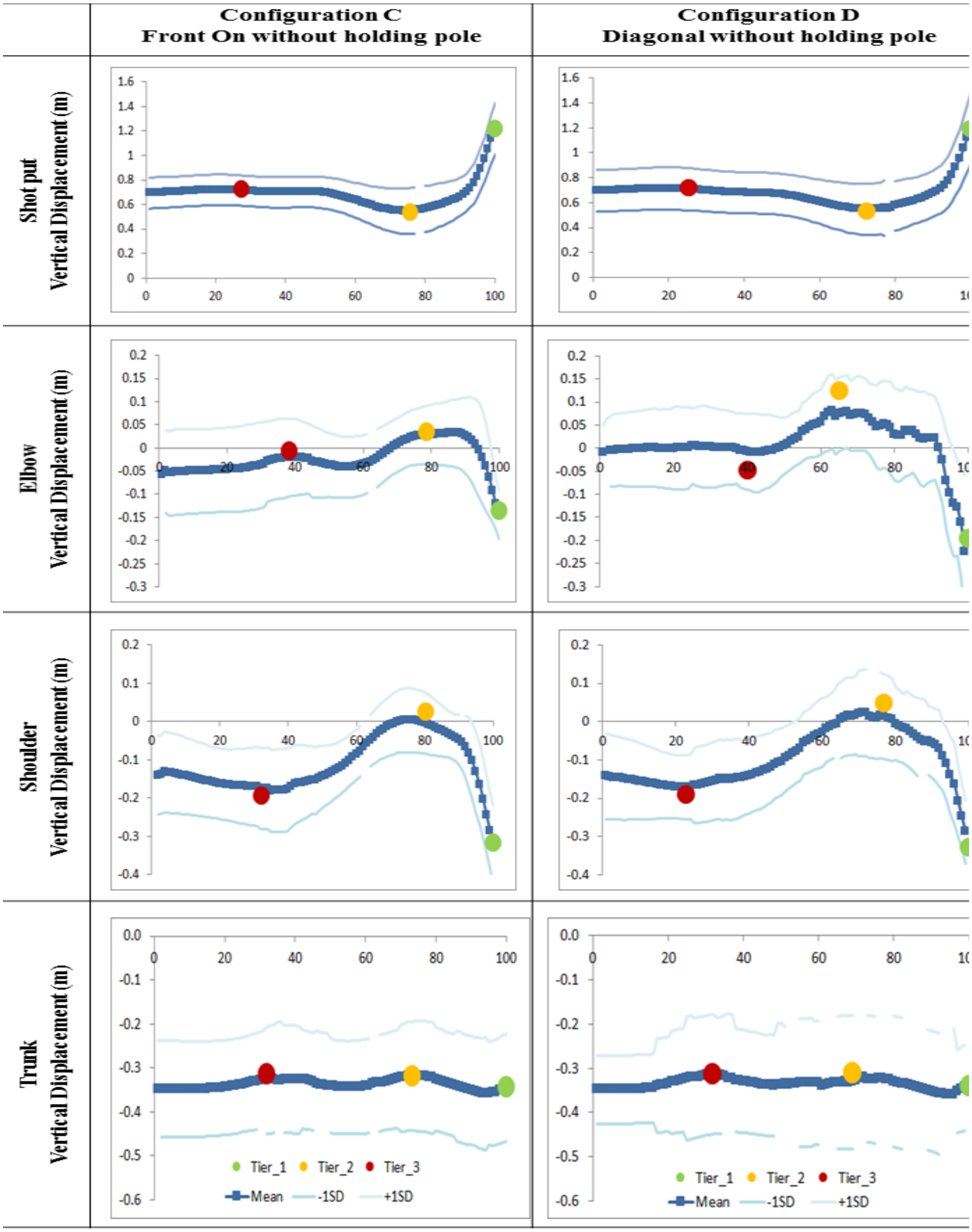
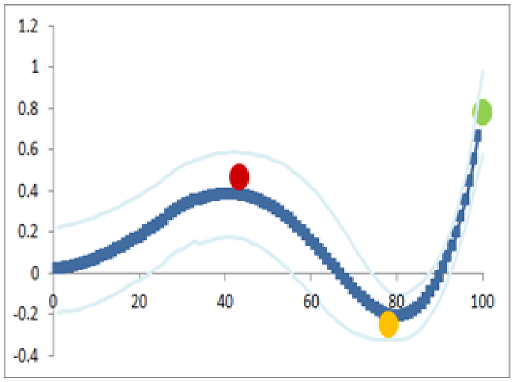
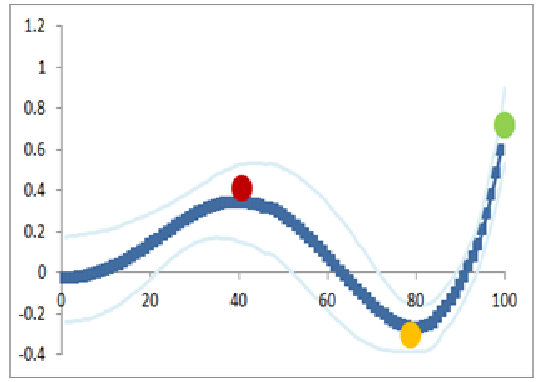
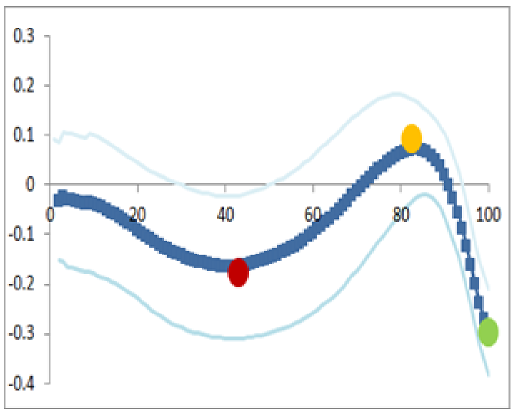
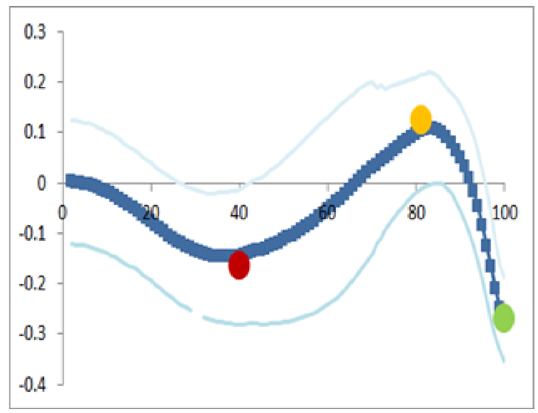
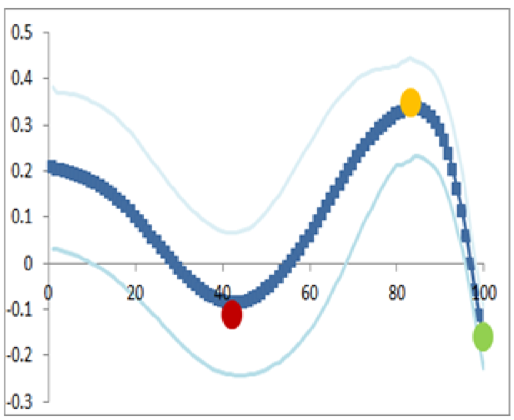
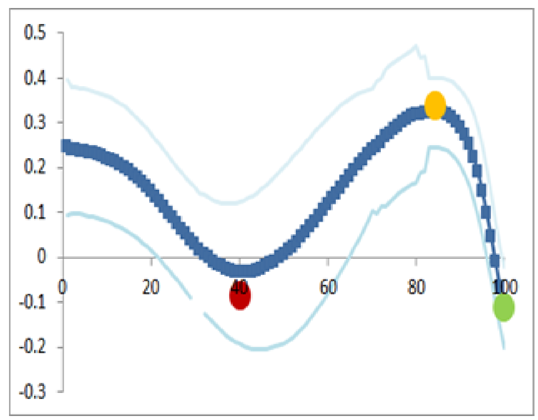
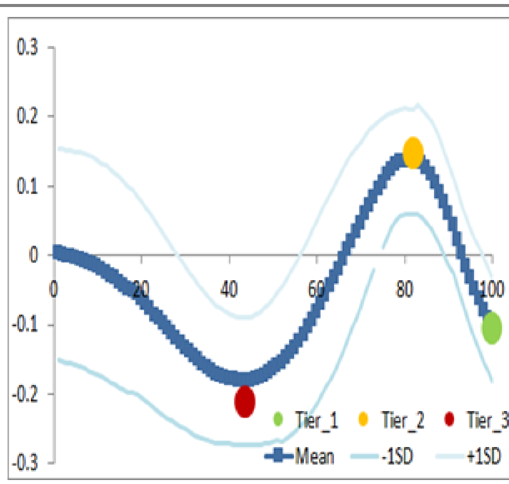
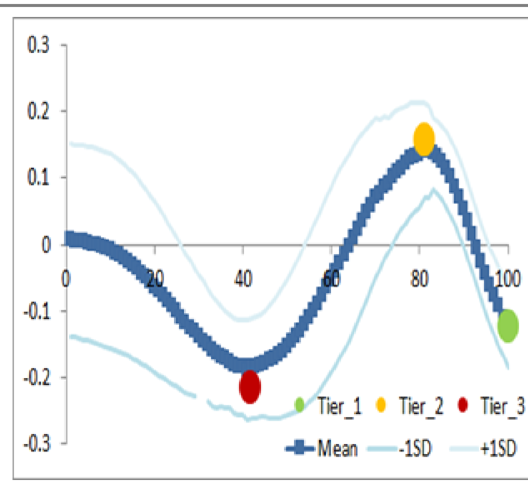


Figure E 1: Progression of the mean and standard deviation of all throws of the vertical displacement expressed in m of shot-put, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (Release), 2 (Power) and 3 (1st Prep) for each seating Configuration A, B, C and D.

<table>
<tr><th></th><th>Configuration A
Front On with holding pole</th><th>Configuration B
Diagonal with holding pole</th></tr>
<tr><td>Shot put
Horizontal Displacement (m)</td><td>
</td><td>
</td></tr>
<tr><td>Elbow
Horizontal Displacement (m)</td><td>
</td><td>
</td></tr>
<tr><td>Shoulder
Horizontal Displacement (m)</td><td>
</td><td>
</td></tr>
<tr><td>Trunk
Horizontal Displacement (m)</td><td>
</td><td>
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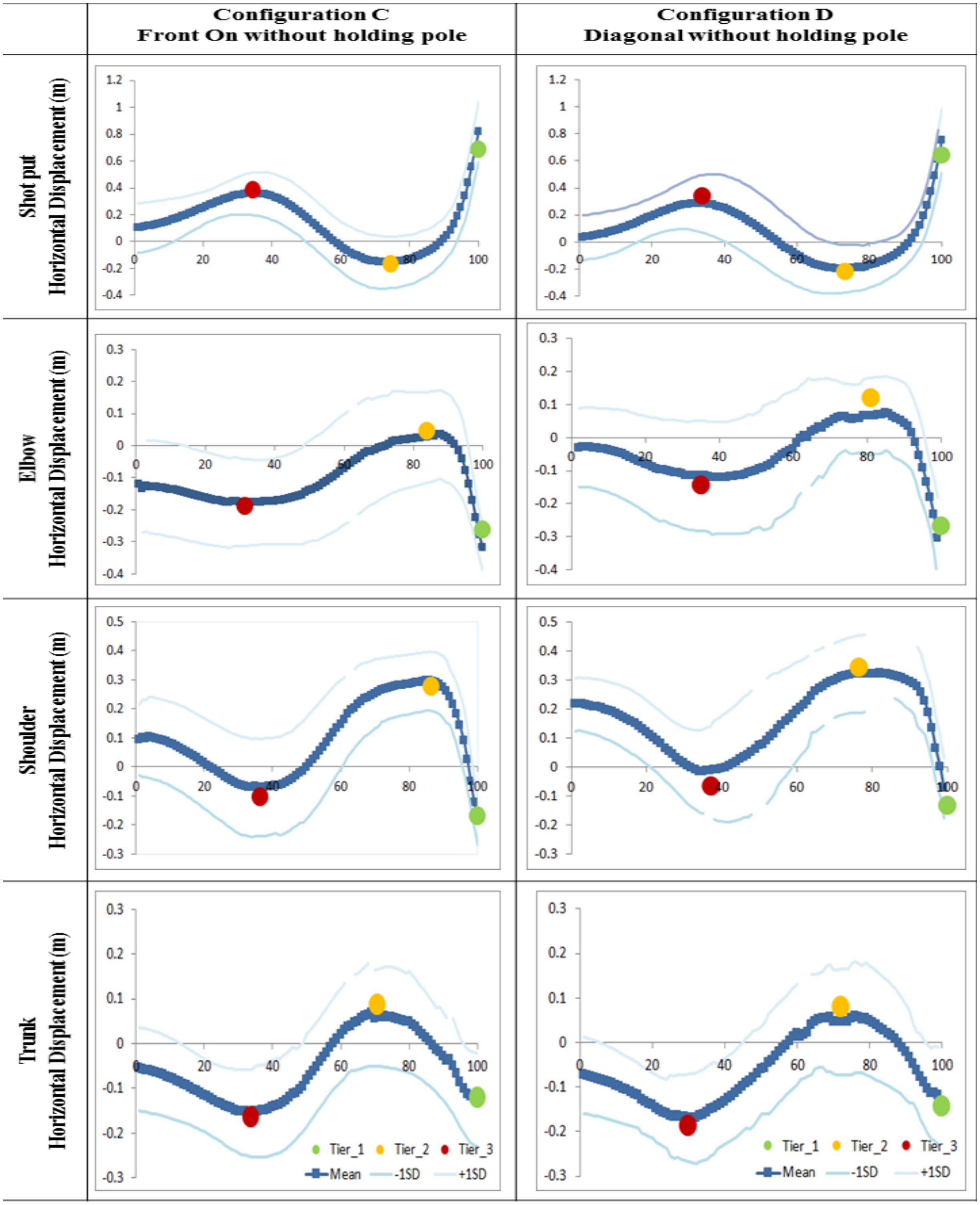
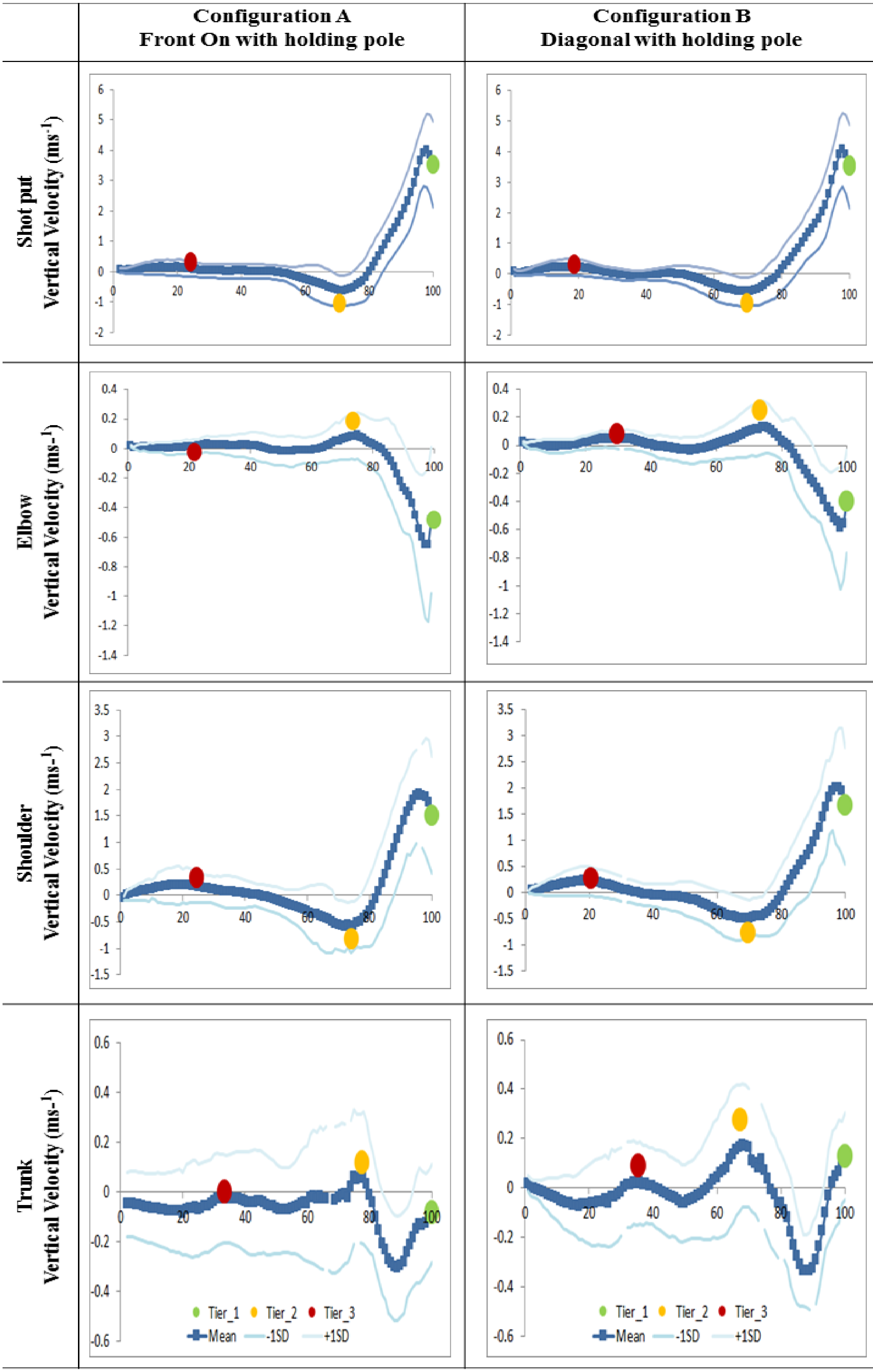


Figure E 2: Progression of the mean and standard deviation of all throws of the horizontal displacement expressed in m of shot-put, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (Release), 2 (Power) and 3 (1st Prep) for each seating Configuration A, B, C and D.


Configuration A
Front On with holding pole
Configuration B
Diagonal with holding pole
Shot put
Vertical Velocity (ms-1)
Elbow
Vertical Velocity (ms-1)
Shoulder
Vertical Velocity (ms-1)
Trunk
Vertical Velocity (ms-1)
Tier_1 Tier_2 Tier_3
Mean -1SD +1SD
Tier_1 Tier_2 Tier_3
Mean -1SD +1SD

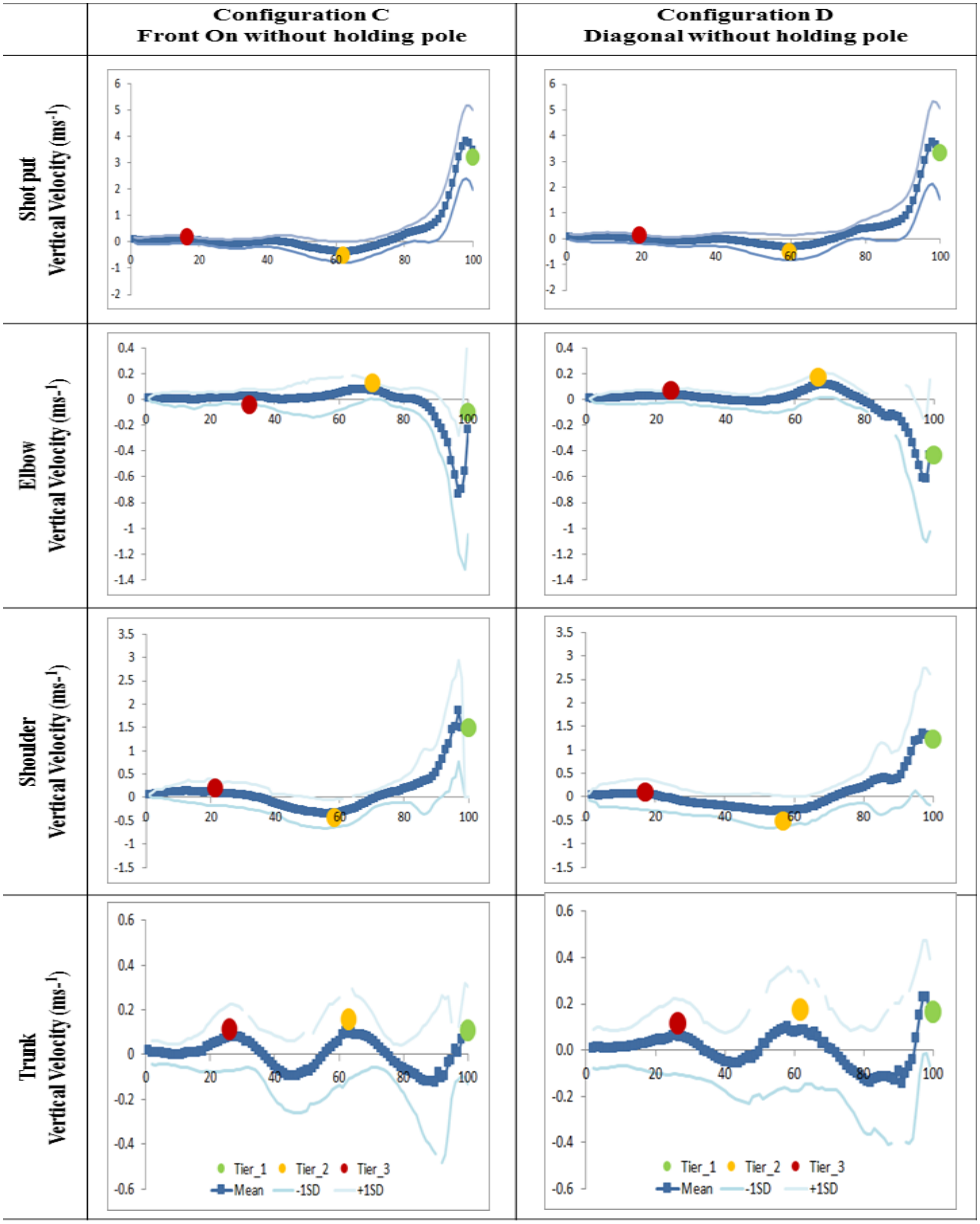
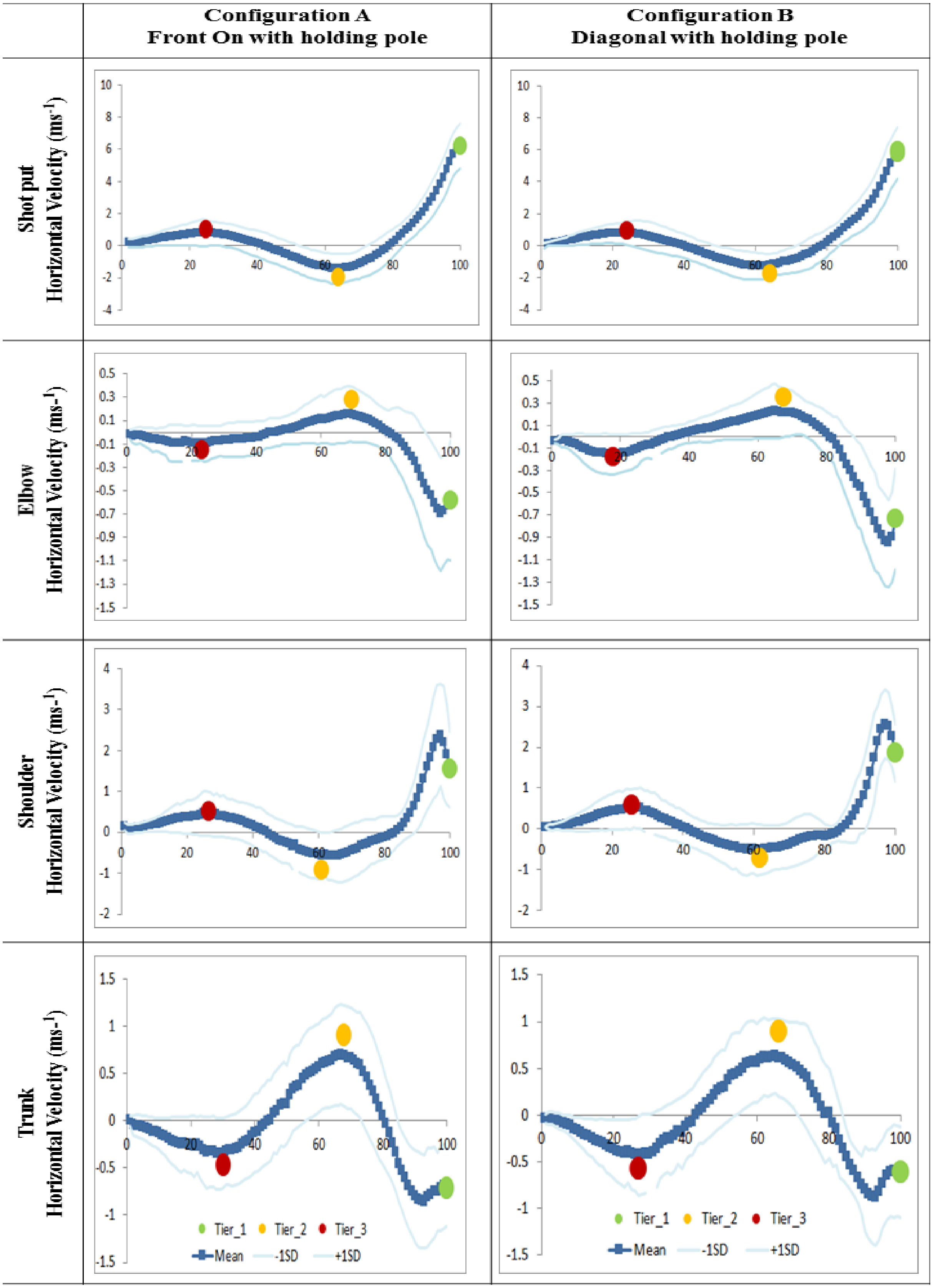


Figure E 3: Progression of the mean and standard deviation of all throws of the vertical velocity expressed in ms^{-1} of shot-put, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (Release), 2 (Power) and 3 (1^{st} Prep) for each seating Configuration A, B, C and D.


Configuration A
Front On with holding pole
Configuration B
Diagonal with holding pole
Shot put
Horizontal Velocity (ms-1)
Elbow
Horizontal Velocity (ms-1)
Shoulder
Horizontal Velocity (ms-1)
Trunk
Horizontal Velocity (ms-1)
Tier_1 Tier_2 Tier_3
Mean -1SD +1SD

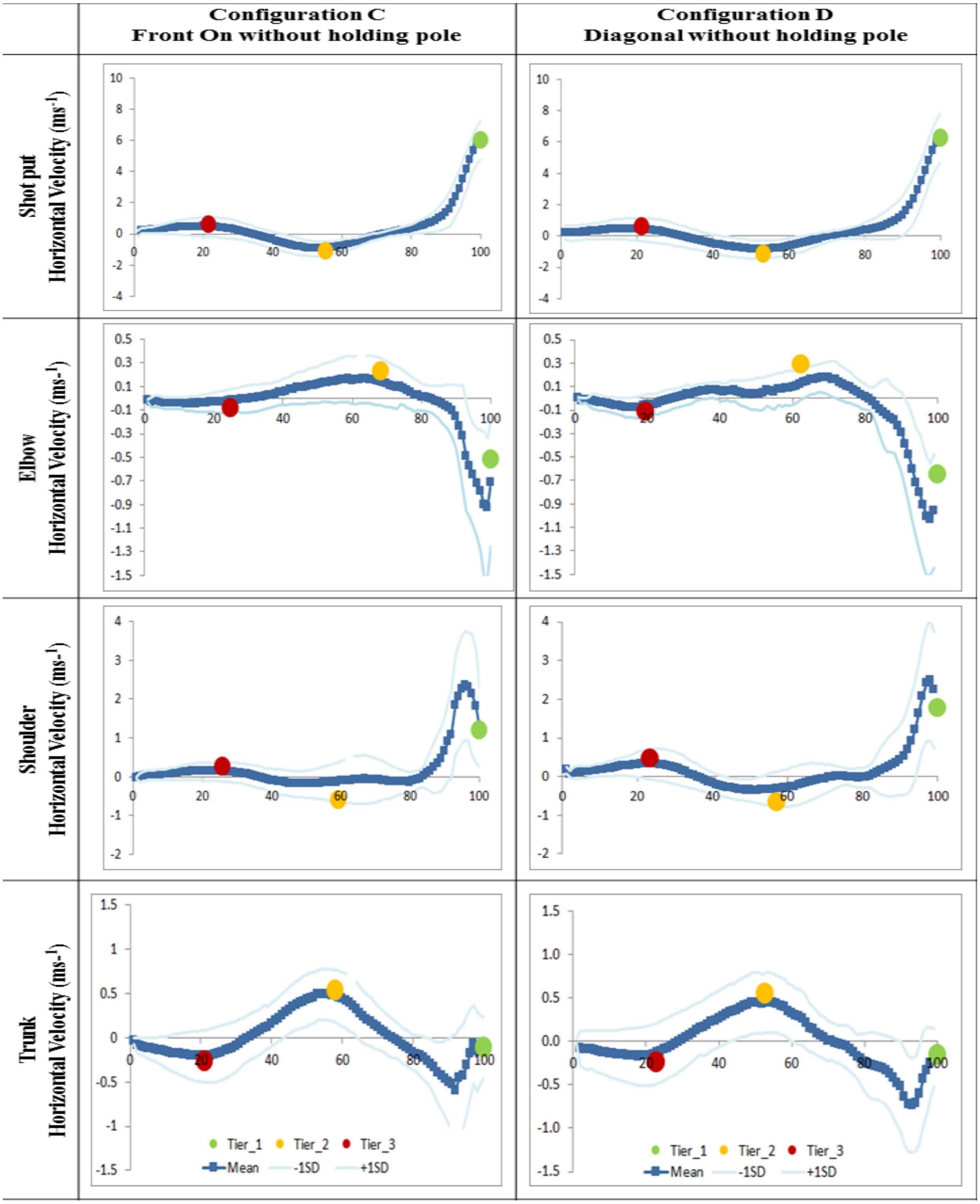


Figure E 4: Progression of the mean and standard deviation of all throws of the horizontal velocity expressed in ms^{-1} of shot-put, elbow, shoulder and trunk over the throw time expressed in percentage of throwing time (%TT) including magnitude at Tiers 1 (Release), 2 (Power) and 3 (1^{st} Prep) for each seating Configuration A, B, C and D.