MAXIMISING BALL RELEASE SPEED IN OVERHEAD THROWING THROUGH OPTIMISING ARM SEGMENT MASSES

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

The tapering distribution of segment masses in the human arm helps in the generation of high ball release speeds in overarm throwing. However, the masses of the individual arm segments might not be optimal; arm segment masses could be optimised in order to improve throwing performance. The aim of this project was to identify and understand the optimal upper arm mass that results in the highest ball release speed in overarm throwing.

The first study was a theoretical study, using a simple two-segment model of the arm to determine the optimal combination of arm segment masses that maximises ball release speed. This simplified throw was chosen to identify the basic mechanism causing changes in ball release speed with a heavier upper arm mass. The study identified that there is an optimal upper arm mass, but this optimum depends on the forearm mass and the shoulder torque. Furthermore, the study showed that a heavier forearm mass produces a lower ball release speed.

An experimental approach was used in the second study to analyse the effect of additional upper arm mass on ball release speed and throwing mechanics in an overarm throw similar to that used by baseball pitchers. However, group analysis of the ball release speed did not reveal an optimal upper arm mass, and most of the kinematic, kinetic, and temporal variables were not affected by additional upper arm mass. However, analysing the ball release speed of each participant individually revealed that most participants increased their ball release speed, although there was considerable variation in the optimal upper arm mass. As the optimal upper arm masses in this study did not agree with those predicted in the first theoretical study, a

more realistic three-dimensional model is needed to simulate the effect of upper arm mass on ball release speed.

The third study was a combination of a theoretical and experimental approach. A three-dimensional model of the throwing arm was used to predict the participant's optimal upper arm mass and to determine the kinematic and kinetic variables that determine the optimal upper arm mass in overarm throwing. Even though the simulations did not accurately predict an athlete's optimal upper arm mass, the results highlighted that throwing athletes can benefit from a heavier upper arm mass as long as their ability to produce a high internal shoulder rotation angular velocity is not restricted.

In summary, the findings of this project highlight that some athletes can benefit from a heavier upper arm mass to maximise their ball release speed without increasing the risk of injuries. However, as the optimal upper arm varies between athletes it is important to analyse each athlete individually.

Table of contents

List of figures

List of tables

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Chapter 1: General introduction

Throwing a projectile is a skill used in sports such as baseball, cricket, and javelin throw where the aim is to throw as fast or as far as possible. As performance in throwing sports mainly depends on the release velocity (Linthorne, 2006), athletes aim to maximise their release velocity. Skilled throwers achieve high release velocities through a sequential proximal-to-distal movement of body segments (Putnam, 1993; Serrien & Baeyens, 2017). The mass distribution of the human body starting with the heavy trunk, followed by the lighter upper arm and forearm, and ending with the very light hand segment (de Leva, 1996; Dempster, 1955) supports the generation of a high projectile release velocity through conservation of angular momentum. Due to the differences in segment mass, the lighter distal segments reach higher angular velocities as the heavier proximal segments decelerate, and reach angular velocities that are higher than the velocity that can be produced by the arm muscles acting in isolation (Naito & Maruyama, 2008).

Even though the anthropometric parameters of an athlete can affect the kinetic chain of overarm throwing, only limited research has analysed how changes in arm segment mass affect throwing performance. Angular momentum is the product of angular velocity and moment of inertia (which is affected by the mass distribution). Athletes can generate a higher angular momentum in a segment by increasing the angular velocity of the segment or by increasing the moment of inertia of the segment (Serrien & Baeyens, 2017). Most studies analysing overhead throwing have focussed on improving ball release speed through various strength training programs (van den Tillaar, 2004). Improving throwing velocity through optimising the mass of the arm segments has attracted far less attention.

Southard (1998) analysed the effect of additional mass attached to the arm segments on ball release speed. The participants in this study had to throw a baseball as fast as possible with eight different segmental mass conditions. The additional mass was attached to the participant's upper arm, forearm, or hand, or with combinations of additional mass on several segments. The upper arm mass was increased on average by 1.4 kg, which represents an average increase in upper arm mass by about 60% of the participant's actual upper arm mass. Additional mass attached to the participant's upper arm was the only condition that resulted in an improved ball release speed (by about 6.4%). The less skilled throwers in the study benefited from additional upper arm mass the most because they improved their proximal-to-distal sequence of maximum segment linear velocities. Increasing the upper arm mass caused the hand segment of the less skilled throwers to lag behind the forearm segment, thus resulting in a higher ball release speed. Attaching additional mass to the distal segments resulted in a decrease in ball release speed.

After (Southard, 1998) showed that additional upper arm mass could increase ball release speed in overarm throwing, Kim, Dounskaia, Hinrichs, and Richard (2008) analysed how different masses attached to either the upper arm or forearm affect horizontal arm swing velocity. These researchers increased the arm segment masses by 25%, 50%, 75%, and 100%, while the participants had to swing their arm as fast as possible in the horizontal plane in order to produce a movement similar to that performed by baseball batters. Attaching an additional 25% and 50% to the upper arm mass resulted in a slight increase in horizontal arm swing velocity, whereas a 75% and 100% increase resulted in a lower arm swing velocity. Additional mass attached to the forearm resulted in lower arm swing velocities, thus confirming the findings of Southard (1998) that a heavier distal segment has a negative effect on throwing performance.

The findings of Southard (1998) and Kim et al. (2008) suggest that athletes could increase their ball release speed with a heavier upper arm mass. Therefore, there must be an optimal upper arm mass that results in the highest ball release speed. Linthorne, Eckardt, Heys, and Reynolds (n.d.) tested this concept in a modified javelin throw, using an 800 g javelin training ball and a two-step run-up. The participants in this study increased the distance thrown by around 5.4% with the optimal amount of mass attached to the upper arm. The optimal upper arm mass varied between participants and ranged from an additional 0.21 kg to 0.60 kg attached to the participant’s upper arm. Also, these results were broadly confirmed by a simple two-dimensional two-segment torque-driven model of throwing (Linthorne et al., n.d.).

Although the benefit of a heavier upper arm mass has been identified in overarm throwing (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), there were several limitations of these studies that should be addressed before the concept of optimising the upper arm can be employed by throwing athletes. None of the studies examined the changes in throwing mechanics that occur with additional upper arm mass. Southard (1998) analysed linear velocity of arm segments with additional upper arm mass, but no study has analysed the changes in joint angles, joint angular velocities, joint torques, and joint forces with increasing upper arm mass. The study by Kim et al. (2008) focused on the horizontal arm swing velocity and the main objective of Linthorne et al. (n.d.) was to confirm that there is an optimal upper arm mass in javelin throw. Due to the planar movement performed in the study of Kim et al. (2008) and the use of two-dimensional video analysis by Linthorne et al. (n.d.), these studies did not analyse kinematic or kinetic data. Analysis of kinematic and kinetic variables with changes in upper arm mass could help to understand mechanisms that cause the increase in throwing performance. Furthermore, Linthorne et al. (n.d.) observed an optimal upper arm mass when throwing for maximum distance, but no study has examined if the same applies when throwing for maximum ball release speed.

The study by Linthorne et al. (n.d.) is the only one that used a computer model to examine the effect of additional upper arm on throwing performance. A simple two-dimensional model of a two segment arm (upper arm and forearm), driven by constant shoulder and elbow torques, was used to simulate a javelin throw. Even though this model broadly replicated the results recorded in the throw experiment, a more realistic representation of the throwing motion would provide further insight into how changes in upper arm mass affect overarm throwing. Therefore, simulating the effect of upper arm mass on ball release speed using a three-dimensional full-body model could help to understand the underlying mechanisms. Furthermore, Linthorne et al. (n.d.) only changed the upper arm mass in the throw simulations. A study that combined changes in upper arm mass with changes in forearm mass, ball mass, shoulder torque, and elbow torque could provide further information about how these variables interact to affect ball release speed and the optimal upper arm mass.

Therefore, the main aim of the present project was to determine the optimal mass of an athlete's upper arm when throwing for maximum velocity and to understand the underlying mechanisms. The secondary aim was to identify if athletes can safely optimise their upper arm mass without increasing their risk of injuries. These aims were tested in three related studies:

- The first study used a modelling approach, creating a two-segment two-dimensional torque-driven computer model of the dominant arm. Overarm throws with changes in upper arm mass, forearm mass, and shoulder torque were simulated to determine the optimal relation between upper arm mass and forearm mass in overarm throwing. It was expected that there is an optimal upper arm mass that results in the highest ball release speed. Ball release speed was expected to decrease as the forearm mass increases.
- In the second study an experimental approach was used to analyse the effect of additional upper arm mass on ball release speed and throwing mechanics. The aim of the second study was to determine the optimal upper arm mass in overhead throwing and to analyse how a heavier upper arm mass affects joint kinematic, kinetic, and temporal variables. A series of masses was attached to a participant's upper arm while throwing as fast as possible. It was expected that a heavier upper arm mass does not result in changes in kinematic variables, but increases the joint forces and joint torques acting on the joints of the dominant arm.
- The third study consisted of two parts. The first part consisted of three-dimensional simulations of throwing in order to predict the effect of additional upper arm mass on ball release speed and throwing mechanics. In the second part, overarm throws performed with additional upper arm mass were analysed to confirm the findings of the throw simulations. The aim of the third study was to identify the characteristics of an individual's throwing technique

that determine their optimal upper arm mass. It was expected that an athlete's optimal upper arm mass could be predicted from the throw simulations and that several kinematic and kinetic variables could be identified that determine an athlete's optimal upper arm mass.

Chapter 2: Literature review

2.1. Throwing a projectile

Throwing a projectile is a skill our human-like ancestors developed millions of years ago. The ability to throw allowed our ancestors to defend themselves and hunt for prey, thus increasing their likelihood of survival (Young, 2009). No other species is able throw as fast, as far, and as accurate as humans (Roach, Venkadesan, Rainbow, & Lieberman, 2013). Throughout evolution, humans developed several musculoskeletal and neurological adaptations that distinguished them from other primates and enabled them to develop the skill of throwing (Calvin, 1982; Isaac, 1987; Larson, 2015; Roach, Lieberman, Gill, Palmer, & Gill, 2012; Roach & Richmond, 2015a, 2015b). Today, throwing a projectile is used in sports such as baseball, cricket, or javelin throw. Professional baseball pitchers release the ball at velocities of around 130 km/h (Theobalt, Albrecht, Haber, Magnor, & Seidel, 2004), cricket bowlers reach ball release speeds in excess of 140 km/h (Worthington, King, & Ranson, 2013), and javelin throwers reach distances of nearly 100 m (Bartlett, 2000).

2.2. Human evolution and projectile throwing

Previous research suggests that skilled overarm throwing played a crucial role in human evolution as it allowed humans to hit a target (enemy or prey) from a distance, thus reducing the risk (Isaac, 1987) and increasing their chances of survival (Young, 2009). Compared to chimpanzees, humans possess a taller, more mobile waist, lower humeral torsion, and a more laterally orientated glenohumeral joint, which allows humans to generate high projectile speeds (Roach et al., 2013). Furthermore, the fully opposable thumb combined with the shorter fingers in the human hand allow for a tight grip of the projectile and an accurate control of release (Young, 2003). Even though these evolutionary adaptations allowed our ancestors to throw projectiles at very high speeds, previous research suggests, that the human body might not be optimal and that a higher upper arm mass could allow athletes to increase their ball release speeds (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). Comparing the mass of some of the projectiles thrown by our ancestors to the mass of the projectiles used in today's sports might suggest that the arm segment masses of humans could be optimal for throwing objects used by our ancestors for hunting and defence. Objects believed to be used by our ancestors as projectiles are generally heavier (80 g to 1550 g) (Isaac, 1987) compared to projectiles used in various sports (Baseball: 145 g; Water polo: 420 g) (Bartlett, 2000).

2.3. Classifications of throws

Athletes use various techniques when throwing a projectile depending on their sport. In general, throws are classified as either overarm, sidearm, or overarm (*Figure 2-1*). The overarm throw is most commonly used in sports and is characterised by the trunk leaning away from the throwing arm and the arm placed above the shoulder (Whiteley, 2007). Overarm throws are used in sports such as cricket, javelin throw, and American football. A sidearm throw is similar to an overarm throw, except that the trunk stays relatively straight and the arm is placed horizontally to the upper body (Whiteley, 2007). In an underarm throw, the athlete leans their trunk to the side of their throwing arm, which is positioned below the shoulder (Matsuo, Takada, Matsumoto, & Saito, 2000). In baseball and handball, all three types of throws are employed by athletes (Matsuo et al., 2000; Wagner, Buchecker, Von Duvillard, & Müller, 2010).

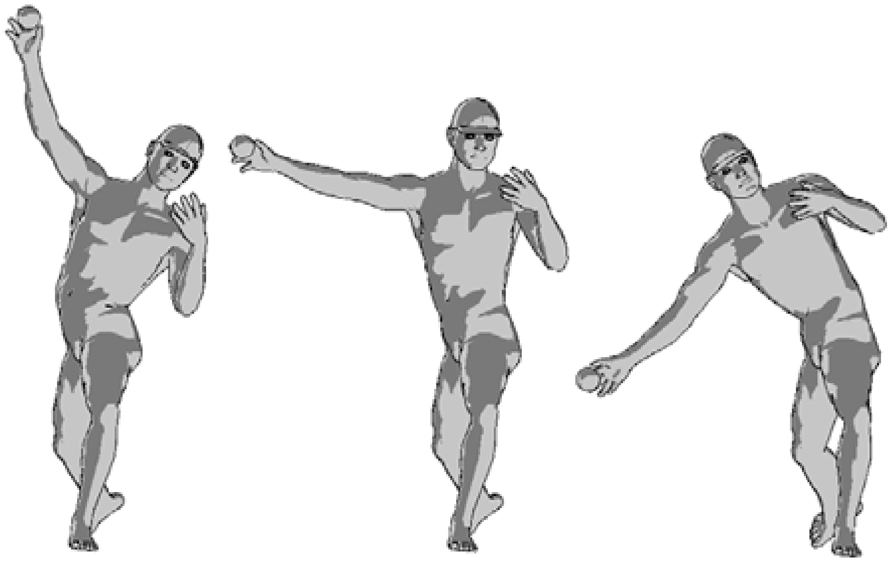

Figure 2-1: Illustrations of throwing classifications in baseball pitching. The left picture shows an overarm throw. The middle picture displays a sidearm throw. The right image shows an underarm throw. (Adapted from Matsuo et al., 2000)

2.4. Determinants of throwing performance

The success of a throw is determined by the release conditions. The three release conditions that affect the trajectory of a projectile are: release speed, release angle, and release height (Figure 2-2).

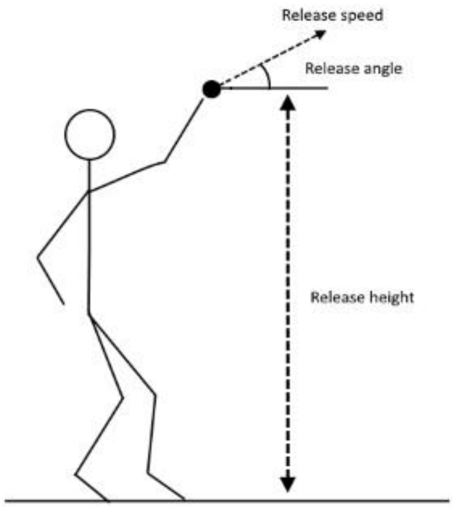

Figure 2-2: Release parameters while throwing a projectile

2.4.1. Release angle

The trajectory of a projectile follows a parabolic shape in the absence of aerodynamics, and so depends on both release angle and release speed (Bartlett, 2000). In many sports the main goal of throwing a projectile is to maximise the distance thrown. In the absence of aerodynamics and with the projectile landing at the same height as it is released and without any anatomical constraints, the optimal release angle is 45°. However, in most sport events the optimal release angle is considerably less than 45° because athletes can generate higher release velocities with smaller release angles (Linthorne, 2006).

In other sports, like basketball for example, where the main aim of the projectile is accuracy rather than distance thrown, the optimal release angle has been reported to be between 45° and 55°, depending on the distance between the ball release and the basket (Brancazio, 1981; Hay, 1985). Because in basketball the ball has to pass through the basket from the top, the optimal release angle is substantially higher than the ones measured in other sports.

In baseball or cricket, for example, the aim of the throw is to leave the opponent with the least time possible to react to the flight of the ball, thus heavily relying on the release speed. A study in cricket observed release angles of 6° to 8° when throwing a ball over 20 m with the aim to reduce the flight time as much as possible, and 8° to 18° when throwing the ball over 40 m (Cook & Strike, 2000). In cricket bowling, release angles of around -6° have been reported for fast bowlers (Cork, Justham, & West, 2012). In baseball, pitchers could use similar release angles as reported in cricket as they release the ball from a 0.254 m high mound, resulting in the target potentially being lower or at the same height as the release height (Nissen et al., 2013). Fastballs in baseball have been reported to be released with a vertical release velocity of around -2 m/s, meaning that the pitcher is throwing the ball slightly downwards to reach the strike zone (Alaways, Mish, & Hubbard, 2001).

2.4.2. Release height

In projectile motion, the release height is the difference between the height at which the projectile is released and the height of landing or the height of the target. Projectiles that are released with the same release angle and release speed will reach a larger distance when thrown from a higher release height. The landing height mainly depends on the rules of the respective sport. In sports such as shot put or javelin throw, the projectile lands on the ground. Therefore, the release height is the same as the same as the height at which the projectile is released, which depends on the athlete’s shoulder height and their arm position as they release the projectile (Linthorne, 2006).

In baseball, however, as the aim of the throw is to reach the strike zone in the shortest possible time, the target that the ball has to reach is positioned above the ground. Additionally, the pitcher is starting his pitching motion while standing on a 0.254 m high mound, thus affecting the release height (Nissen et al., 2013). The technique used by baseball pitchers allow them to have a very low release angle, which results in a relatively low release height.

2.4.3. Release speed

The release speed of a projectile is the most important determinant of throwing performance as the range achieved is multiplied by four if the release speed doubles (Bartlett, 2000). Therefore, most athletes, independent of their sport, aim at increasing their release speed of the projectile thrown. As previously mentioned, due to anatomical restraints, humans are able to produce higher release speeds at lower release angles (Linthorne, 2006). As a result, in order to be able to increase their release velocity, athletes in various sports reduce their release angles (Linthorne, 2001; Linthorne & Everett, 2006; Linthorne & Stokes, 2014).

In baseball, the release speed determines how much time the batter has to react to the flight of the ball. The flight time of an average fastball has been reported to be around 0.45 s (Alaways et al., 2001). Therefore, slight increases in release speed can have a big effect on the success of a pitched ball, as it will leave the batter with even less time to react. As baseball pitches are released with a very low release angle and from a very low release height, release speed becomes even more important as the target is nearly straight ahead from the point of release. Additionally to the release speed, aerodynamics also influence the speed of the ball as it approaches the batter. A reduction in speed of 3% to 7% of ball speed has been reported by the time the batter hits the ball (Alaways et al., 2001). Examples of ball release speeds of several sports involving throwing a projectile and the corresponding mass of the ball are presented in Table 2-1.

Table 2-1: Release speeds reached in various sports and the mass of the projectile thrown (Bartlett, 2000).

Sport	Release speed (m/s)	Mass of the projectile (g)
Baseball	50	145
Basketball	18	600
Cricket	35	156
Shot put	15	7260
Softball	44	188
Volleyball	30	270
Water polo	15	420

2.5. Phases of throwing

In order to reach high ball release speeds, highly skilled throwers require precise coordination of sequential proximal-to-distal movement of the individual body segments (Serrien & Baeyens, 2017). Researchers analysing overhead throwing divide the movement into several phases, separated by key events in order to facilitate analysis (Bartlett, 2000). In general, the movement consists of three distinct phases, which are separated by key events. The first phase is the preparation phase, which puts the body segments into a position to benefit from the kinetic chain and stores elastic energy (Bartlett, 2000). This is followed by the action phase, which accelerates the projectile through the sequential movement of body segments (Bartlett, 2000). The last phase is recovery phase during which the body segments decelerate in order to reduce the risk of injury (Bartlett, 2000).

However, due to differences in throwing techniques used in different sports, several studies have described more sport specific phases in baseball pitching (Dillman, Fleisig, & Andrews, 1993; Werner, Fleisig, Dillman, & Andrews, 1993), American football passing (Fleisig et al., 1996), cricket bowling (Bartlett, Stockill, Elliott, & Burnett, 1996), handball (Wagner et al., 2010), tennis (Hansen et al., 2017) and baseball batting (Fleisig, Hsu, Fortenbaugh, Cordover, & Press, 2013). As the goal of the throws performed in the experimental studies of this project is to throw as fast as possible, the throws will be divided into the six phases as previously described for baseball pitching (Dillman et al., 1993; Werner et al., 1993). These six phases are windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through, which are divided by lead foot contact, maximum external shoulder rotation, ball release, and maximum internal shoulder rotation (Figure 2-3).

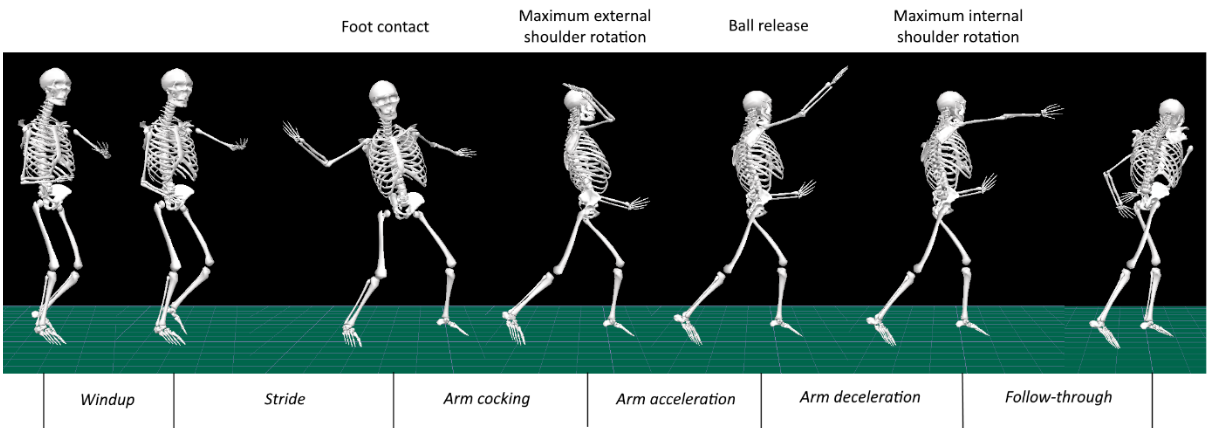

Figure 2-3: Six phases of throwing in baseball pitching and throwing in American football.

2.5.1. Windup

The windup starts with the shifting of the thrower's weight on to the support leg, which is the contralateral leg to the throwing arm in skilled throwers (Dillman et al., 1993). Lifting of the lead leg is followed by the trunk rotating away from the intended target, and ends with the stride leg moving towards the target (Werner et al., 1993).

2.5.2. Stride

The stride phase begins with the stride leg movement and ends with the front foot contact (Werner et al., 1993). During this phase, the thrower's weight shifts towards the target. In order to benefit from the trunk rotation to contribute to the ball release speed, the trunk should not rotate towards the target yet (Dillman et al., 1993). Additionally, the stride length should be long enough in order to result in sequential rotation of the hip followed by trunk rotation, which is crucial in order to increase throwing velocity (Crotin, Bhan, & Ramsey, 2015) and reduce the risk of injury (Aguinaldo, Buttermore, & Chambers, 2007; Fortenbaugh, Fleisig, & Andrews, 2009).

2.5.3. Arm cocking

The arm cocking phase starts with the front foot contact and ends with the maximum external shoulder rotation, which lasts for 0.10 s to 0.15 s in baseball pitchers (Fleisig & Escamilla, 1996). During this phase, the pelvis and trunk rotate towards the target, while the arm lags behind, resulting in maximum external shoulder rotation. Throughout the arm cocking phase, the optimal shoulder abduction is around 90° (Matsuo, Matsumoto, Mochizuki, Takada, & Saito, 2002). Shortly before highly skilled throwers reach maximum external shoulder rotation angle, the elbow is extended in order to increase the moment of inertia of the arm to further increase the external shoulder rotation angle (Stodden, Langendorfer, Fleisig, & Andrews, 2006). Deviating from the proximal-to-distal sequence, as elbow extension occurs before internal shoulder rotation, puts the different arm segments in a position to benefit the most from the changing moment of inertia (Hirashima, Yamane, Nakamura, & Ohtsuki, 2008). The correct arm position combined with a lower humeral torsion measured in baseball pitchers enables highly skilled throwers to increase the elastic energy stored at the shoulder during this phase (Roach et al., 2013; Taylor et al., 2009).

2.5.4. Arm acceleration

The arm acceleration phase is the dynamic phase between the maximum external shoulder rotation and the instant of ball release (Werner et al., 1993). During this phase internal shoulder rotation initiates and the elbow extends (Fleisig & Escamilla, 1996). Highly skilled throwers further extend their elbow, enhancing an athlete's ability to reach high internal shoulder rotation angular velocities of up to 10,000°/s (Werner et al., 2007) by decreasing the arm's moment of inertia around the longitudinal axis of the upper arm (Dillman et al., 1993). The ability of skilled throwers to optimise the moment of inertia of the throwing arm during the arm cocking and arm acceleration phases highlights the importance of the limb posture in order to reach a high ball release speed (Hirashima et al., 2008).

2.5.5. Arm deceleration

After the athlete releases the ball, internal shoulder rotation and elbow extension continues until the instant of maximum internal shoulder rotation (Dillman et al., 1993). This phase is called arm deceleration as the internal shoulder angular velocity and elbow extension angular velocity decreases and reaches zero.

2.5.6. Follow-through

The follow-through starts with maximum internal shoulder rotation and ends when the athlete reaches a balanced position (Fleisig & Escamilla, 1996). Even though this phase does not contribute to the ball release speed, a correct follow-through is important in order to reduce the risk of injury (Fleisig, Andrews, Dillman, & Escamilla, 1995). Movement of the large body segments such as the legs and trunk assist the reduction of energy in the throwing arm in order to reduce the loads especially on the shoulder and the elbow (Fleisig et al., 1995).

2.6. Kinetic chain

The different phases of throwing are characterised by a coordinated sequential movement of body segments, which is known as the kinetic chain (Putnam, 1993). A kinetic chain involves movement of several segments, where the position and movement of one segment depends on the position and movement of its neighbouring segments (Chu, Jayabalan, Kibler, & Press, 2016). A kinetic chain can either be performed as a push-like or throw-like movement (Blazevich, 2007). A push-like movement is characterised by the segments of the kinetic chain all moving at the same time; whereas for a throw-like movement, a proximal-to-distal sequence of segment movements is observed. Overarm throwing is performed using a throw-like kinetic chain with the movement starting from the legs and finishing at the hand when the projectile is released (Chu et al., 2016). This coordinated movement allows highly skilled throwers to reach high ball release speeds due to conservation of angular momentum between the body segments (Serrien & Baeyens, 2017).

2.6.1. Conservation of angular momentum

Angular momentum (H) is the product of moment of inertia (I) and angular velocity (ω):

$$H = I\omega$$

As a movement is initiated at the proximal segment, the angular momentum is transferred to the distal segment as the proximal segment slows down. In human movements such as overarm throwing, conservation of angular momentum results in very high velocities of the most distal segments due to inertial parameters of the body segments. In the early phases of the movement, the heavy proximal segments generate large amounts of angular momentum. As the proximal segment slows down, the angular velocity of the lighter distal segment increases, due to the lower moment of inertia. In overarm throwing, the legs and trunk generate large amounts of angular momentum. After the trunk rotation slows down, the angular velocity at the shoulder increases due to the lower upper arm mass. The same principles applies at the elbow and the wrist, resulting in very high ball release speeds.

2.6.2. Kinetic chain of throwing

The kinetic chain in overarm throwing is initiated by the heavy proximal segments (the trunk), followed by the lighter distal segments (the arm segments), resulting in the distal segments rotating faster than the proximal segments (Chu et al., 2016). Throughout the kinetic chain, highly skilled throwers combine the inertial parameters of their body segments and conservation of angular momentum to reach high ball release speeds (Serrien & Baeyens, 2017). As a result, the outcome of the kinetic chain is related to the magnitudes of joint torques, joint angular velocities, and joint angles (Hirashima et al., 2008). Even though overarm throwing is a fluent movement of coordinated movement between body segments, research has focussed on key characteristics that has been related to throwing performance. A review of key characteristics involved in the kinetic chain of overarm throwing will be provided.

2.6.2.1. Inertial parameters of the kinetic chain

Skilled throwers are able to generate high ball release speeds by transferring angular momentum from their proximal segments to their distal neighbours (Putnam, 1993). Due to the inertial parameters of each body segment along the kinetic chain, humans manage to increase the angular velocity of the distal segments as the proximal segments slow down (Chu et al., 2016). Baseball pitchers generate high amounts of linear and angular momentum through rotation of the trunk segment during the arm cocking and acceleration phases (Lin, Su, Nakamura, & Chao, 2003), which are caused by the heavy mass of the trunk. The trunk segment accounts for around 43% to 50% of the total body mass (de Leva, 1996; Dempster, 1955). Due to conservation of angular momentum, the angular velocity of the lighter upper arm segment increases. The same principle applies between the upper arm and the forearm, and between the forearm and the hand. The mass of the arm segments are substantially lower than the mass of the trunk segment. The upper arm mass accounts for less than 3% of the total body mass, the forearm accounting for less than 2% of the total body mass, and the hand segment around 0.5% of the total body mass (de Leva, 1996; Dempster, 1955).

Analysis of the segmental muscle volumes of baseball pitchers reveals differences in upper arm muscle volume of their dominant arm compared their non-dominant arm and compared to football players (Yamada, Masuo, Nakamura, & Oda, 2013). Additionally, a higher upper arm muscle volume in baseball pitchers has been related to higher ball release speeds (Yamada, Yamashita, et al., 2013). The changes in upper arm muscle volume in baseball pitchers could affect their ability to reach high ball release speeds.

2.6.2.2. Temporal variables

Correct timing of key events during baseball pitching is crucial in order to reach high ball release speeds and reducing the risk of injury (Seroyer et al., 2010). The whole pitching motion starting from the wind-up until the instant of ball release takes around 1.0 s (Freeston, Ferdinands, & Rooney, 2015). However, the phases during which the arm moves towards the target, the arm cocking and arm acceleration phases, only take around 0.15 s to 0.30 s (Stodden, Fleisig, McLean, & Andrews, 2005; Urbin, Fleisig, Abebe, & Andrews, 2013; Werner, Suri, Guido, Meister, & Jones, 2008), with the arm acceleration phase taking only around 0.04 s (Freeston et al., 2015). The majority of the studies that analyse temporal variables in baseball pitching report the relative timing of a key event as a percentage of the throwing motion, starting from stride foot contact (0%) to ball release (100%).

Baseball pitchers reach maximum torso angular velocity at around 49% to 52% of the total pitch time depending on their skill level (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001). Maximum external shoulder rotation occurs at around 81% during the pitching motion, followed by maximum elbow extension angular velocity at 91% to 95% (Matsuo et al., 2001; Stodden et al., 2005). Maximum internal shoulder angular velocity occurs shortly after the ball is released at around 102% to 104%, occurring earlier during the throw for more skilled throwers (Matsuo et al., 2001).

In addition to the timing of several key variables during the throwing motion, the correct timing between some of these events have also been identified to affect ball release speed. Baseball pitchers that increased the time between maximum pelvis angular velocity and maximum trunk angular velocities managed to reach higher ball release speeds (van der Graaff et al., 2016). Additionally, differences in the time between joint movements were observed in children of various ages. In a group of children that mastered the proximal-to-distal sequence, older children reduced the time between shoulder and elbow movement, resulting in higher ball release speeds (Southard, 2009).

Even though the proximal-to-distal sequence of movements has been described to result in the highest ball release speeds (Serrien & Baeyens, 2017), this sequence has not been observed in skilled baseball pitchers (Hirashima et al., 2008). Elbow extension occurs before internal shoulder rotation in order to reduce the moment of inertia of the throwing arm and favour the production of high internal shoulder rotation angular velocities (Hirashima et al., 2008).

2.6.2.3. Legs

In throwing, the legs provide the stable base for the kinetic chain and are crucial in producing high ball release speeds and decreasing the risk of injury (Seroyer et al., 2010). When developing the skill of throwing, children employ various strategies in order to increase ball velocity (Langendorfer & Roberton, 2002; Roberton & Konczak, 2001). Whereas young children perform no step at all when throwing a ball, more developed children use a small or ipsilateral step to increase their ball release speed (Lorson & Goodway, 2008). The most advanced throwers use a long contralateral step, which reaches values of around 74% to 87% of the thrower's body height in baseball pitchers and 61% in American football passing (Fleisig et al., 1996; Matsuo et al., 2001). Correct stride length is also crucial in reducing the risk of injury in baseball pitchers as it affects the timing of both the trunk and upper arm rotations when baseball pitchers reduce their stride length to around 50% of their body height (Crotin et al., 2015; Ramsey & Crotin, 2016; Ramsey, Crotin, & White, 2014).

In baseball pitching, the posterior ground reaction force of the stride leg during the arm cocking phase has been identified to be related to wrist velocity as it brakes the movement of the legs and allows the trunk to move forward (McNally, Borstad, Onate, & Chaudhari, 2015). At the instant of stride foot contact, baseball pitchers flex their stride leg knee to around 40° to 51° before extending the knee to around 28° to 43° (Fleisig et al., 1996, 1999; Kageyama, Sugiyama, Kanehisa, & Maeda, 2015; Kageyama, Sugiyama, Takai, Kanehisa, & Maeda, 2014). The knee angle of the stride leg at both the instants of stride foot contact and ball release have been identified to affect ball release speed, with more skilled baseball pitchers increasing their knee extension range of motion (Kageyama et al., 2014; Werner et al., 2008). Additionally, baseball pitchers that reach higher ball release speeds generate higher knee extension angular velocities compared to their counterparts that throw less fast (Kageyama et al., 2014; Matsuo et al., 2001).

2.6.2.4. Trunk

Apart from the trunk being the heaviest segment in the throwing kinetic chain and thus at the base of generating angular momentum, there are other characteristics that are essential in our ability to throw. Humans have a taller, more mobile waist compared to our closest relatives the chimpanzees, which facilitates the rotation between the hips and the thorax (Bramble & Lieberman, 2004; Roach et al., 2013). These decoupled body segments permit humans to generate angular momentum through their legs and transfer it to their upper body. An increased range of motion between the hips and the thorax combined with the relatively heavy mass of the trunk, assists humans in producing and storing elastic energy at the shoulder (Roach et al., 2013), which assists in generating high ball release speeds.

The heavy and flexible trunk allows skilled throwers to use a differentiated trunk rotation where the pelvis rotates forwards while the upper part of the spine still rotates away from the target before eventually rotating forwards as well (Langendorfer & Roberton, 2002). Less developed throwers use no trunk rotation at all; only forward-backward trunk movement or block trunk rotation (Roberton & Konczak, 2001; Yan, Payne, & Thomas, 2000). An athlete’s trunk movement while throwing a projectile not only affects the position and velocities of the trunk and pelvis, but also affects the motion of the more distal body segments (Urbin, Stodden, & Fleisig, 2013). Differentiated trunk rotation reduces the maximum shoulder horizontal adduction angle while increasing the maximum external shoulder rotation angle, and angular velocities at the shoulder and elbow (Urbin, Stodden, et al., 2013).

In professional baseball pitchers, trunk axial rotation reaches angles of 55° (Aguinaldo et al., 2007; Fleisig et al., 2013). Collegiate and adolescent baseball pitchers employ less trunk axial rotation of around 45° to 48° in the build-up of the throw (Kageyama et al., 2015, 2014). At the instant of ball release, professional baseball pitchers use more trunk forward tilt compared to their collegiate or adolescent counterparts. Professional baseball pitchers reach forward trunk angles of around 122° while collegiate and adolescent baseball pitchers reach angles of around 100° to the vertical (Fleisig et al., 1996; Kageyama et al., 2015, 2014). The increase in forward tilt range of motion observed in professional baseball pitchers enables them to accelerate the ball over a longer distance (Stodden et al., 2005). Professional baseball pitchers reach trunk axial velocities of around 1200°/s (Fleisig et al., 1999; Matsuo et al., 2001), and maximum forward trunk tilt angular velocities of around 630°/s have been recorded for collegiate baseball pitchers (Kageyama et al., 2015). Additionally, higher trunk angular velocities have been identified to contribute to higher ball release speeds (Dowling, Pearl, Laughlin, Tubbs, & Fleisig, 2016).

2.6.2.5. Shoulder

In throwing, the shoulder joint is one of the major contributors to performance as it connects the heavy trunk to the lighter arm segments, thus being responsible for storing and transferring elastic energy (Roach et al., 2013). In baseball pitching, the elastic energy stored at the muscles and tendons crossing the shoulder joint accounts for up to 54% of internal shoulder rotation work, thus enabling skilled throwers to reach joint angular velocities that surpass the power production capacities of the internal shoulder rotator muscles (Roach et al., 2013). As the upper arm lags behind the forward movement of the trunk, skilled throwers benefit from the conservation of linear and angular momentum as well as the stretch-shortening cycle of the muscles in order to maximise their ball release speed (Serrien & Baeyens, 2017).

Employing the proximal-to-distal sequence allows skilled throwers to reach maximum external shoulder rotations of around 182° by professional baseball pitchers (Sabick, Torry, Kim, & Hawkins, 2004), around 125° for baseball catchers throwing while sitting on their knees (Plummer & Oliver, 2014), and around 164° in professional American football quarterbacks (Fleisig et al., 1996). Baseball pitchers have been shown to retain a lower humeral torsion in their throwing arm compared to non-throwing athletes (Roach et al., 2012). Furthermore, differences in humeral torsion have also been observed between the throwing arm and the non-throwing arm of professional baseball pitchers. A lower humeral torsion means that through passive stretching baseball pitchers reach greater maximum external shoulder rotation (throwing arm: 135°; non-throwing arm: 126°) and lower maximum internal shoulder rotation (throwing arm: 69°; non-throwing arm: 78°) in their throwing arm compared to their non-throwing arm, while the total range of motion remains the same (throwing arm: 203°; non-throwing arm: 204°) (Borsa et al., 2005). Similar results have been found in experienced handball players (Fieseler, Jungermann, Koke, Delank, & Schwesig, 2014).

A throwing athlete's ability to reach large external shoulder rotation angles during the arm cocking phase enables them to generate internal shoulder rotation angular velocities of up to 10,000°/s in professional baseball pitchers (Werner, Gill, Murray, Cook, & Hawkins, 2001), around 5000°/s in American football quarterbacks

(Fleisig et al., 1996), and around 2500°/s in handball players (Serrien, Clijsen, Blondeel, Goossens, & Baeyens, 2015; van den Tillaar & Ettema, 2009). As most throwing-related studies simplify the shoulder joint complex and reduce it to the glenohumeral joint, the internal shoulder rotation is calculated in relation to the trunk. A throwing study that incorporated scapula and clavicle movement into their shoulder model recorded maximum internal shoulder rotation angular velocities of around 3100°/s in baseball pitchers (Gasparutto, van der Graaff, van der Helm, & Veeger, 2015). Previous studies have identified that the maximum internal shoulder angular velocity is related to high ball release speeds (Fleisig et al., 1999; Hirashima, Kudo, Watarai, & Ohtsuki, 2007; Werner et al., 2008).

A study analysing the interaction torques acting on the throwing arm of baseball pitchers revealed, that the high internal shoulder rotation angular velocities are produced by a combination of joint torques and interaction torques generated through movement of the proximal segments (Hirashima, Kudo, Watarai, et al., 2007). The interaction torques at the shoulder joint result in the maximum internal shoulder angular rotation occurring close to the instant of ball release, even though only a small amount of internal shoulder rotation torque is generated when an athlete releases the ball (Hirashima et al., 2008).

Furthermore, several studies have identified the importance of the shoulder abduction angle throughout the arm cocking and arm acceleration phase in baseball pitching (Matsuo et al., 2002; Stodden et al., 2005). In overarm baseball pitching the average shoulder abduction angle during the arm acceleration phase is between 90° and 100° (Fleisig et al., 1996; Stodden et al., 2005) and the optimal shoulder abduction angle at the instant of ball release is at around 90° (Matsuo et al., 2002;

Matsuo, Matsumoto, Takada, & Mochizuki, 1999). Using a three segment simulation model, Matsuo et al. (2002) found that the peak in wrist velocity occurred at shoulder abduction angles ranging between 80° and 114° for both overarm and underarm baseball pitchers.

2.6.2.6. Elbow

Throughout the majority of the arm cocking phase, the elbow is flexed at around 90° in baseball pitchers (Dun, Fleisig, Loftice, Kingsley, & Andrews, 2007; Fleisig et al., 1999; Werner et al., 1993), extending shortly before the instant of ball release to around 20° of elbow flexion (Fleisig et al., 1996). Experienced baseball pitchers reach elbow extension angular velocities of around 2400°/s (Dun et al., 2007), handball players reach velocities of around 1200°/s (Serrien et al., 2015), and American football quarterbacks reach velocities of around 1800°/s (Fleisig et al., 1996).

In overhead throwing, the elbow extension is mainly produced by interaction torques generated through movement of the trunk and the upper arm (Hirashima et al., 2008). The importance of the interaction torques in elbow extension are also highlighted by the arm position and timing of joint rotations in baseball pitchers. Flexing the elbow to around 90° throughout the arm cocking phase increases the moment of inertia of the throwing arm, resulting in the upper arm lagging behind the trunk movement and enabling skilled throwers to increase the maximum external shoulder rotation angle (Stodden et al., 2006). As elbow extension in baseball pitchers occurs before internal shoulder rotation, the moment of inertia around the longitudinal axis of the upper arm is reduced, thus facilitating internal shoulder rotation through interaction torques (Hirashima et al., 2008).

Forearm pronation/supination does not play a major role in generating ball release speeds (Hirashima & Ohtsuki, 2008). During the arm cocking phase, the forearm is supinated to around 17° before pronating by around 24° at the instant of ball release (Barrentine, Matsuo, Escamilla, Fleisig, & Andrews, 1998). The peak forearm pronation angular velocity occurs during the arm deceleration phase and reaches values of around 5200°/s (Barrentine et al., 1998).

2.6.2.7. Wrist

In overarm throwing, the wrist movement does not contribute much towards the ball release speed (Hirashima, Ohgane, Kudo, Hase, & Ohtsuki, 2003). When throwing a fastball in baseball, pitchers reach wrist flexion angular velocities of around 3000°/s during the arm acceleration phase (Barrentine et al., 1998). Even though the wrist is flexed at instant of ball release, the wrist muscles still produce wrist extension (Hirashima, Kudo, Watarai, et al., 2007). However, the interaction torques generated at the forearm counteract the muscle torques and so keep the wrist joint relatively stable at the instant of ball release (Hirashima et al., 2003), in order to avoid affecting the force-producing capabilities of the finger muscles, which are responsible to accurately release the ball (Hore, Watts, Leschuk, & MacDougall, 2001).

2.7. Injuries in overarm throwing

Apart from looking at improving performance, research on baseball pitching is also concerned with reducing the risk of injury. Even though the rate of injuries in college baseball is one of the lowest compared to other sports (Hootman, Dick, & Agel, 2007), mainly because of the low percentage of player contact injuries (Dick et al., 2007), the high percentage of injuries in baseball pitchers justifies research into injury prevention in overarm throwing. A report on Major League Baseball from 1989 to 1999 highlighted that pitchers in particular are susceptible to injuries, and accounted for 48% of all injuries during this time period (Conte, Requa, & Garrick, 2001). Similar percentages have been reported from 2002 to 2008, and 67% of the pitchers' injuries occurred at the upper extremity (Posner, Cameron, Wolf, Belmont, & Owens, 2011). Around 30% of these injuries occur at the shoulder joint, and around 25% occur at the elbow joint (Conte et al., 2001; Posner et al., 2011). Therefore, identifying factors that increase the risk of injury in overarm throwing is crucial for professional throwing athletes.

2.7.1. Kinetic variables associated with injuries

Overuse injuries in overarm throwing are caused by high forces and torques acting frequently on the joints of the throwing arm (Fortenbaugh et al., 2009). As well as the maximum internal shoulder rotation torque, maximum shoulder compression force and maximum elbow valgus torque have also been associated with injuries in baseball pitchers (Fleisig et al., 1995). Shoulder compression forces of about 1100 N (about 108% of a professional baseball pitcher's body weight) have been recorded close to the instant of ball release (Fleisig et al., 1995; Werner et al., 2001).

Maximum elbow valgus torque of about 120 N·m in professional baseball pitchers (Buffi, Werner, Kepple, & Murray, 2015; Werner et al., 1993) and about 20 N·m in youth baseball pitchers (Sabick, Torry, Lawton, & Hawkins, 2004) occur during the arm cocking phase at the same time as maximum internal shoulder rotation torque, which reaches values of about 100 N·m (Anz et al., 2010; Sabick, Torry, Kim, et al., 2004).

In professional baseball pitchers, maximum internal shoulder rotation torque has been identified as causing higher shoulder compression force (Werner et al., 2001), but has not been associated with high shoulder compression force in college baseball pitchers (Werner et al., 2007). Maximum shoulder abduction torque affects the generation of higher shoulder compression force as well (Werner et al., 2007, 2001). Furthermore, maximum internal shoulder rotation torque affects elbow valgus torque in professional baseball pitchers and youth baseball pitchers (Sabick, Torry, Lawton, et al., 2004; Werner, Murray, Hawkins, & Gill, 2002). In general, the previously mentioned studies suggest that in order to reduce the risk of injury, athletes have to reduce their joint torques and joint forces while maintaining the same ball release speed.

2.7.2. Kinematic variables associated with injuries

Increases in kinetic variables of overarm throwing are caused by several kinematic variables and thus are pathomechanical (Fortenbaugh et al., 2009). In professional baseball pitchers, high shoulder compression force is caused by the maximum external shoulder rotation angle, and the elbow angle at the instant of lead foot contact and at the instant of ball release (Werner et al., 2001). The importance of the elbow flexion angle to reduce shoulder compression force is also observed in college baseball pitchers, as well as the maximum horizontal shoulder adduction angle (Werner et al., 2007).

Elbow valgus torque is affected by elbow flexion angle, maximum external shoulder rotation angle, shoulder abduction angle, and horizontal shoulder adduction angular velocity in baseball pitchers of various levels and ages (Aguinaldo & Chambers, 2009; Sabick, Torry, Lawton, et al., 2004; Werner et al., 2002). Furthermore, Matsuo et al. (2002) performed three-dimensional throw simulations to determine the optimal shoulder abduction angle that increases performance and reduces the elbow valgus torque. Even though a different optimal shoulder abduction angle was observed for each participant, the study highlighted that baseball pitchers already employ shoulder abduction angles that minimise the stresses on the shoulder and elbow joints (Matsuo et al., 2002).

2.7.3. Temporal characteristics associated with injuries

Efficient use of the kinetic chain allows baseball pitchers to decrease forces and torques that act on the joints of the throwing arm, while reaching high ball release speeds (Fortenbaugh & Fleisig, 2009). Aguinaldo et al. (2007) observed lower internal shoulder rotation torques in professional baseball pitchers compared to less experienced baseball pitchers. A later onset of trunk rotation allowed the professional baseball pitchers to reach higher ball release speeds, while also generating less internal shoulder rotation torque. Similar findings have been observed in relation to the elbow valgus torque. Baseball pitchers that started rotating their trunk before lead foot contact produced a higher elbow valgus torque compared to the pitchers that delayed trunk rotation (Aguinaldo & Chambers, 2009). Athletes that manage to increase the transfer of energy from the trunk to the throwing arm through proper throwing mechanics need to generate less torque at the shoulder and elbow to reach the same ball release speed, and hence have a lower risk of injury (Seroyer et al., 2010).

2.8. Experimental vs. simulation design

In biomechanics, either an experimental or a simulation approach can be used to analyse and describe movements. An experimental approach provides information about kinematic and kinetic variables of the analysed movement (Pandy, 2001). Simulation studies typically use a simplified representation of the physical system in order to determine how changes to a variable affect the movement or other variables analysed (Yeadon & King, 2008). The approach used depends on the research questions.

2.8.1. Pros and cons of different study designs

Both experimental and simulation study designs have advantages and disadvantages, which should be taken into consideration before planning a study. The advantage of an experimental approach is that researchers are analysing actual movement irrespective of the instructions the participants are given (Yeadon & King, 2008). Even if the researcher instructs the participant to change certain aspects of their movement, a realistic movement will still be recorded. However, the disadvantage of an experimental approach is that attempting to change one variable might affect several other variables (Yeadon & King, 2008).

Employing a simulation approach enables researchers to design an ideal theoretical experiment, which allows them to change a single variable and analyse the effect this has on the movement (King & Yeadon, 2015). A disadvantage of such an approach is that the analysed movement does not represent the actual movement of a participant. Changing a certain variable of a participant's movement could potentially result in a different outcome to the results obtained from computer simulations.

2.8.2. Force-velocity relationship

The maximum force that a muscle can generate depends on the velocity at which the muscle is contracting. In the concentric phase, higher forces are produced at low velocities and lower forces at higher velocities, whereas in the eccentric phase, higher forces are generated at high velocities (Yeadon, King, & Wilson, 2006). This relationship affects humans' ability to generate joint torques and thus impacts movements such as overarm throwing (Kentel, King, & Mitchell, 2011).

2.8.3. Computer models of the upper body

Various studies have used computer models to analyse throwing in order to improve throwing performance or prevent injuries. The shoulder joint complex in particular causes some challenges to researchers. The shoulder joint complex consists of three joints; the glenohumeral joint, the acromioclavicular joint, and the sternoclavicular joint. These joints link the trunk to the humerus, scapula, and clavicle (Terry & Chopp, 2000). Due to the complexity of the human shoulder, a lot of research has focussed on developing accurate shoulder models to analyse arm movement.

2.8.3.1. Shoulder models used in throwing studies

In three-dimensional throwing studies, most researchers employed a simplified shoulder model that restricts movement to the glenohumeral joint (Fleisig et al., 1996; Hirashima, Kudo, Watarai, et al., 2007; Hong, Cheung, & Roberts, 2001; Hore, Debicki, Gribble, & Watts, 2011; Keeley, Oliver, & Dougherty, 2012; Roach & Lieberman, 2014). The main reason for using a simplified shoulder model is the difficulties of accurately tracking the scapula with skin markers during fast arm movements because of the displacement between the scapula and the skin (Veeger, Chadwick, & Magermans, 2003).

Several studies have used an electromagnetic tracking device to record scapula movement (Meyer et al., 2008; Myers, Laudner, Pasquale, Bradley, & Lephart, 2005; Oliver & Weimar, 2015) or reflective skin markers tracked by high speed cameras (Miyashita, Kobayashi, Koshida, & Urabe, 2010). However, all of these studies acknowledged the limitations of their procedures caused by potential skin movement. A study by Gasparutto et al. (2015) used regression equations to estimate the glenohumeral joint centre and the movement of the scapula to analyse the joint velocities at the shoulder produced by Dutch baseball pitchers.

2.8.3.2. Joint rotation sequence in throwing studies

Apart from differences in the shoulder models used in throwing studies, researchers have used various joint rotation sequences for the shoulder joint when analysing overarm throwing. The most commonly used rotation orders are the ISB-recommended YXY sequence (Gasparutto et al., 2015; Keeley et al., 2012) and the XYZ sequence (Dillman et al., 1993; Feltner & Dapena, 1986; Fleisig et al., 1996;

Roach et al., 2013). Three-dimensional kinematic analysis of the glenohumeral joint is complicated, due the large range of motion, which can result in gimbal lock (Šenk & Chèze, 2006). However, studies comparing the results of several joint rotation sequences concluded that there is no one sequence that best describes each shoulder rotation while also avoiding gimbal lock (Phadke, Braman, LaPrade, & Ludewig, 2011; Šenk & Chèze, 2006). Therefore, in the present project I decided to follow the ISB recommendations, as they were proposed in order to facilitate comparison between studies (Wu et al., 2005).

2.9. Changes of inertial parameters in overarm throwing

Various aspects of overarm throwing have been analysed in order to understand how humans employ the proximal-to-distal sequence to generate high ball release speeds (Putnam, 1993; Serrien & Baeyens, 2017), improve throwing performance (Fortenbaugh & Fleisig, 2009; Matsuo et al., 2002), and reduce the risk of injury (Aguinaldo et al., 2007; Aguinaldo & Chambers, 2009; Werner et al., 2001, 2002). However, only limited research has been done to analyse how arm segment masses affect overarm throwing. In overarm throwing, the body segment masses facilitate the generation of high ball release speeds because the proximal segments are heavier than the distal segments (de Leva, 1996; Dempster, 1955). Analysing how changes in body segment mass affect overarm throwing could help athlete's to increase throwing performance without increasing the risk of injury.

2.9.1. Upper arm mass

Several studies have analysed the effect that changes in arm segment mass distribution has on the ability to throw a projectile as far or as fast as possible.

Southard (1998) analysed the throwing performance of participants from four different skill levels while attaching additional masses to the different segments of the throwing arm. In this study, the skill levels were based on the participant's ability to perform a proximal-to-distal sequence of segment motions. Attaching an additional 1.4 kg of mass to the participant's upper arm resulted in an increase in ball release speed by 6.4% for the less skilled throwers. The additional upper arm mass enabled the participants to improve their throwing technique as the heavier upper arm mass caused the movement of the distal segments to lag behind the proximal segments.

Kim et al. (2008) attached various masses to the participant's upper arm and they were asked to swing their arm as fast as possible. The researchers observed a slight increase in horizontal arm swing velocity with an upper arm that was increased by 25% and 50% from the participant's actual upper arm mass. The greatest increase in horizontal arm swing velocity was about 1.4% and this was recorded with 50% of additional upper arm mass (about 1 kg). However, increasing the upper arm mass by 75% and 100% of the participant's upper arm mass resulted in a lower horizontal arm swing velocity.

As the studies by Southard (1998) and Kim et al. (2008) observed an increase in performance with a heavier upper arm mass for some of their participants, these findings suggest that there is an optimal upper arm mass that enables athletes to maximise their throwing performance. Linthorne et al. (n.d.) analysed how different amounts of mass attached to the upper arm affect the distance thrown in a modified javelin throw using an 800 g training ball. They found that there is an optimal upper arm mass ranging between 0.21 kg and 0.60 kg of additional mass which produced an average increase in distance thrown by 5.4%. Furthermore, the results of a simple two-segment computer model of throwing broadly agreed with the participant's optimal upper arm mass.

2.9.2. Forearm mass

On the other hand, attaching additional mass to the more distal segments (forearm and hand) of the throwing arm results in a decrease in throwing performance and horizontal arm swing velocity (Kim et al., 2008; Southard, 1998). Increasing the mass of the forearm segment or hand segment results in a decrease in ball release speed (Southard, 1998). A similar decrease also occurred to the horizontal arm swing velocity as the moment of inertia of the arm increases with additional mass attached to the distal segments, thus negatively affecting the end-point velocity (Kim et al., 2008).

2.9.3. Risk of injury

Even though previous studies have analysed the effect of additional upper arm mass on throwing performance (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), no research has focussed on how a heavier upper arm mass would affect an athlete's risk of injury. A simplistic application of Newton's second law of motion suggests that athletes have to generate higher forces and torques with a heavier segment mass so as to produce the same acceleration (Fortenbaugh et al., 2009). However, improvements to the proximal-to-distal sequence and to the mechanical efficiency of the throwing motion could influence the loads acting on the joints and so, heavier segment masses might not necessarily result in an increased risk of injury (Fortenbaugh & Fleisig, 2009). The Improvement in the kinetic chain of less skilled throwers with additional upper arm mass observed by Southard (1998) suggests that these participants also managed to reduce the loads that acted on their joints during the throws. However, further research on how changes in arm segment masses affects joint forces and joint torques is required in order to determine if additional upper arm mass increases the risk of injury in overarm throwing.

2.10. Summary

The ability to throw has been identified as a crucial skill when it came to the survival of our ancestors as it allowed them to hunt for prey and defend themselves (Young, 2009). Throwing ability is facilitated by several anatomical characteristics of the human body (Roach et al., 2013), including the mass distribution of the different body segments, which allows us to benefit from the kinetic chain principle, thus reaching a very high velocity at the hand (the lightest and most distal segment) (Putnam, 1993).

Some studies have suggested that the mass distribution of the segments of the throwing arm can be improved in order to reach a higher ball release speed (Kim et al., 2008; Southard, 1998) and increase the distance thrown (Linthorne et al., n.d.). These studies suggest that athletes can benefit from a heavier upper arm mass, whereas increasing the mass of either the forearm or hand segment results in a decrease in performance. Although these studies highlight the importance of the arm segment masses to an athlete's ability to throw a projectile, only the study by Linthorne et al. (n.d.) suggests that there is an optimal upper arm mass that results in the highest throwing performance and that this optimal mass might be specific to the participant.

Even though several studies have shown that throwing athletes might benefit from a heavier upper arm mass to increase their ball release speed or distance thrown, further research is required in order to determine if athletes should attempt to optimise their upper arm mass. No previous study has analysed how a heavier arm segment mass affects throwing mechanics and how changes in segment mass determine an athlete's optimal upper arm mass. Furthermore, changing arm segment masses in combination with joint torques in a full-body throwing model would provide further information about how arm segment masses are related to an athlete's ability to throw a ball as fast as possible.

The overall aim of the present project was to identify an athlete's optimal upper arm mass in overarm throwing, and to determine if additional upper arm mass affects the risk of injury. The findings of the present project was expected to provide throwing athletes with further evidence on whether they should attempt to optimise the masses of their arm segments.

Chapter 3: Optimal mass of the arm segments in overarm throwing: A 2D simulation study.

3.1. Introduction

The main characteristic of a throwing motion is the kinetic chain. Through the use of this proximal-to-distal sequence, humans are able to throw a projectile with both high velocity and high accuracy (Putnam, 1993; Seroyer et al., 2010). In many sports (eg. baseball, handball, water polo, etc.) the aim is to achieve a very high projectile velocity in order to leave the opponent with little time to react. The kinetic chain in such sports involves the athlete starting the throwing movement with their legs, followed by trunk rotation, before transferring the generated energy to their arm (Roach et al., 2013). This mechanism results in a very high angular velocity of the lighter distal segments as their heavier proximal neighbour segments slow down (Pappas, Zawacki, & Sullivan, 1985).

The proximal-to-distal sequence of body segment movement allows humans to reach higher angular velocities at the distal segments, which cannot be produced by the muscles acting on that segment alone, but are assisted by the movement of the proximal segments (Putnam, 1991). Thus, the motion of a segment depends on the motion and the position of its neighbouring segment (Putnam, 1993). In overarm throwing, several studies have shown that elbow extension is mainly produced by interaction torques generated by the movement at the shoulder, which highlights the importance of optimising the sequential movement along the kinetic chain (Feltner, 1989; Hirashima et al., 2008). Several studies used two-dimensional arm models to determine that a proximal-to-distal onset of either muscle activation (de Lussanet & Alexander, 1997) or joint torques (Herring & Chapman, 1992) lead to the best throwing performance. The latter study confirmed that this joint torque pattern is the best, irrespective of changes to segment characteristics (mass and length). These studies highlight the complex nature of the multisegmental throwing movement, as the central nervous system has to combine coordination of muscle forces and the anthropometric parameters of the different body segments involved. A lot of biomechanical research in overarm throwing has focused on the coordination of muscle forces or joint torques in order to improve throwing performance. However, an area that has only attracted little attention so far in throwing-related studies is the effect that anthropometric parameters have on throwing performance.

The human anatomy, with the segments at the start (eg. trunk) of the kinetic chain being heavier and having a greater moment of inertia than those at the end (eg. forearm, hand) (de Leva, 1996), allows for the generation of high end point velocities, resulting in high projectile release velocities. Several studies observed that changing the mass distribution of the arm segments can lead to increases in throwing performance and improvements in throwing technique (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). However, no study has analysed the optimal distribution of arm segment masses that results in the highest ball release speed.

3.1.1. Inertial parameters in throwing

Many studies have focused on describing the throwing techniques for various sports (Bartlett et al., 1996; Fleisig et al., 1996; Worthington et al., 2013) and how to improve throwing performance through training programs (van den Tillaar, 2004). However, there is limited research on how the inertial parameters of the arm segments affect throwing velocity or throw distance (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). Although the mass distribution of the human arm very likely assists the generation of high release velocities, these studies suggest that the mass distribution might not be optimal. A study by Southard (1998) observed an increase by around 6.4% in ball release speed while attaching around 1.4 kg of additional mass at the centre of mass of the upper arm. An increase by around 1.4% in horizontal arm swing velocity was measured in another study that attached around 1.0 kg to the upper arm (Kim et al., 2008). The authors argue that the relatively low increase in arm swing velocity was caused by the use of the non-dominant arm, which has been shown to affect the ability to regulate interaction torques (Sainburg, 2002). A study by Linthorne et al. (n.d.) observed an increase in throw distances of 1 to 3 m (3-8%) in javelin throwers as additional mass was added to the upper arm of the participants. However, the optimal mass added to the upper arm was specific to each participant.

On the other hand, increasing the mass of the forearm or the hand segment resulted in a decrease in ball release speed (Southard, 1998) and horizontal arm swing velocity (Kim et al., 2008). Kim et al. (2008) explained the decrease in horizontal arm swing velocity by the increase of the system’s moment of inertia, which overpowered the higher muscle torque produced by the participants. A similar effect on the ball release speed was also identified while using a wrist brace in order to restrict the range of motion during an overarm throw (Roach & Lieberman, 2014). As this brace increased the mass at the distal end of the kinetic chain, the throws resulted in a decrease in ball release speed. Studies using a double pendulum simulation of a throwing motion and a double pendulum simulation of a forehand in tennis came to similar conclusions. Throwing heavier balls resulted in a decrease in throwing velocity (Cross, 2004) and a heavier racket led to a decrease in racket tip speed (Cross, 2011). Therefore, identifying an optimal relationship between the upper arm mass and the forearm can assist athletes in generating higher projectile velocities.

3.1.2. Importance of upper limbs in throwing

Although an advanced throwing motion is characterised by an efficient transfer of energy through the whole kinetic chain, the upper limbs play the dominant role in generating a high ball release speed. According to previous research (Toyoshima, Hoshikawa, Miyashita, & Oguri, 1974), 53% of the ball velocity in an overarm throw is produced by the upper limbs. However, other studies, analysing similar throwing motions, have shown that not all the angular rotation of the shoulder, elbow, and wrist joints are produced by the respective muscles crossing these joints (Feltner, 1989; Hirashima et al., 2008; Hong et al., 2001). The rapid joint rotations, especially at the elbow and the wrist, are largely due to interaction torques generated at the heavier proximal segments (Hirashima, Kudo, Watarai, et al., 2007). At the shoulder joint, a substantial amount of the rotation is produced by the various shoulder muscles, whereas the rest is transferred from more proximal segments (Hirashima, Kudo, Watarai, et al., 2007). Similar results were obtained by a study of ball release speed in cricket bowling by Zhang, Unka and Liu (2011). The investigators observed a contribution of up to 50% from the shoulder rotations to the ball release speed. The findings of the previously mentioned studies highlight the importance of upper limb motions in an efficient overarm throw.

3.1.3. Temporal lag of joint rotations in throwing

Temporal lag between the different joint rotations plays an important role in an athlete’s throwing motion. Highly skilled throwers are able to produce a proximal-to-distal sequence of joint rotations in order to maximise the ball release speed (Putnam, 1993). Additionally, a decrease in elbow lag was observed for the most skilled throwers compared to their less skilled counterparts (Southard, 2009). Several studies have focused on the arm motion during throwing and the importance of the temporal lag between elbow and shoulder rotations in order to improve performance and reduce the risk of injury (Fortenbaugh et al., 2009; Matsuo et al., 2001). An increase in time between the peak angular velocities of the upper torso and the elbow extension resulted in a decrease in ball release speed and a decrease in joint torques (Urbin, Fleisig, et al., 2013). However, other studies suggest that athletes can optimise the temporal lag between joint rotations in order to reach the same ball release speed and at the same time decrease the joint kinetics and thus reduce the risk of injuries (Herring & Chapman, 1992). In a three-segment simulation (upper arm, forearm and hand), they demonstrated that the highest release velocity was obtained with the elbow torque onset occurring 200 ms after the onset of the shoulder torque, followed by the wrist torque onset 40 ms after the elbow torque.

These results not only confirm the importance of the temporal lag of a distal segment compared to their proximal neighbour, but also the importance of the correct timing in order to optimise transfer of energy between the segments. Attaching additional mass to the upper arm of less skilled throwers resulted in changes in temporal lag between the different segments (Southard, 1998). Whereas these subjects did not produce a proximal-to-distal sequence of maximum arm segment velocity, a heavier upper arm mass results in a more advanced throwing motion. Therefore, the researchers expect that optimising the arm segment mass distribution results in an improved temporal lag between maximum joint angular velocities that cause an increase in projectile velocity.

3.1.4. 2D throwing models

In biomechanics, computer simulation models are used in order to improve performance or reduce the risk of injuries. These simulations allow for one variable at a time to be changed, thus carrying out ideal theoretical experiments (King & Yeadon, 2015). Computer simulation models can range from very simple two-dimensional models to complex three-dimensional full-body models. The main rule is that the model should be as simple as possible while having the required complexity to allow the research question to be answered (Yeadon & King, 2008). Several studies have used simple two-dimensional rigid body computer models in order to analyse mechanical principles in overarm throwing.

A two-segment arm model was created to analyse the timing of muscle activation onset (Chowdhary & Challis, 1999) and a three-segment model was created to analyse the timing of joint torque onset in throwing (Herring & Chapman, 1992). Reducing the complexity of the models in these studies enabled the researchers to highlight the importance of the proximal-to-distal sequence in order to improve throwing performance. Another study, also using a two-segment arm model to examine the coordination patterns of throwing, suggested that the physical properties of the arm segments have an influence on the proximal-to-distal patterns (Chowdhary & Challis, 2001). Similar outcomes are observed by a study using a three-segment model to analyse interaction torques in throwing, confirming that humans' central nervous system uses the biomechanical properties of the throwing arm in order to achieve higher projectile velocities (Debicki, Watts, Gribble, & Hore, 2010).

The findings of the studies on a multisegmental movement indicate the importance of analysing different arm segment mass distributions in more detail in order to determine their effect on throwing performance and on the throwing motion. In order to isolate each individual variable, a computer simulation model is required in this study. As the main focus of this study is to determine an optimal relationship between the upper arm mass and the forearm mass, a two-dimensional torque-driven arm model with two segments was considered sufficient in order to fulfil the aims of the present study.

3.1.5. Aims of the study

Although previous studies have identified that ball release speed depends on the mass of the arm segments, it is not known if there is an optimal combination of arm segment masses that produces the highest ball release speed. Therefore, the aim of the present study was to determine the combination of upper arm and forearm masses that optimises throwing performance. A two-dimensional computer simulation model of throwing was developed. The two-segment model was driven by a shoulder torque and an elbow torque. The outcome of the present study could be beneficial for athletes that are required to throw a projectile as fast as possible by providing them with information about how arm segment masses could affect their performance.

3.1.6. Hypothesis

Several hypotheses were tested in the present study:

- Ball release speed decreases as forearm mass increases.
- There is an optimal upper arm mass that results in the highest ball release speed.
- The optimal upper arm mass leads to improvements in timing between maximum upper arm angular velocity and maximum forearm angular velocity.

3.2. Methods

A two-dimensional simulation model of throwing was created using Working Model 2D software (Design Simulation Technologies Inc., Canton, MI, USA). The model was driven by joint torques at the shoulder and at the elbow. The torque values in the model were obtained experimentally from a participant performing a similar throwing motion. The throw simulations were run for 320 combinations of upper arm and forearm masses. In addition, five shoulder torque values were investigated, resulting in a total of 1600 simulated throws. A simplified two-dimensional model was chosen for this study in order to investigate whether an optimal arm segment mass exists and investigate the mechanisms that determine the optimal mass distribution. Even though the throwing technique in this simulation study differs from the techniques used by athletes in sports throwing, similar models have been successfully used in order to verify different mechanisms related to the kinetic chain (de Lussanet & Alexander, 1997; Herring & Chapman, 1992).

3.2.1. Participant

One physically active male participant (age: 30 years, height: 1.72 m, mass: 68.0 kg) took part in the study. The participant used his dominant arm (right) to throw a tennis ball at a target. The participant had no advanced expertise in any particular throwing-related activity. The study was conducted in the Biomechanics Laboratory at Brunel University London. The Research Ethics Committee at Brunel University London approved the research protocol, and before the start of the testing a detailed explanation of the protocol was provided to the participant and informed consent was obtained.

The participant's upper arm mass was calculated to be 1.90 kg and his forearm mass 1.09 kg, based on the body proportion data reported by Dempster (1955). Values for the upper arm and forearm masses for adult males of different masses are presented in Table 3-1. The moment of inertia about an axis through the centre of mass of each arm segment was adjusted according to the mass of each segment used in the simulated throws, using the following equation:

$$I = m * (K_{cg} \times segment\ length)^2$$

where I is the moment of inertia, m is the segment mass and K_{cg} is the radius of gyration about the centre of mass.

Table 3-1: Arm segment masses for people of different body masses (Dempster, 1955).

	Body mass (kg)	Upper arm mass (kg)	Forearm mass (kg)
Participant	68.0	1.90	1.09
Adult male	50.0	1.40	0.80
	75.0	2.10	1.20
	100.0	2.80	1.60

3.2.2. Experimental Setup

At the start of the data collection session, reflective markers were placed on the upper body of the participant (Figure 3-1). Eleven markers were placed on the anatomical landmarks and the segments of the trunk and dominant arm in order to calculate joint angles. Two additional markers were attached on either side of a tennis ball (58 g), which was used as the throwing projectile in order to calculate ball velocity. A tennis ball was used in this study rather than a heavier ball in order to avoid any discomfort or injuries, due to the slightly unusual throwing technique.

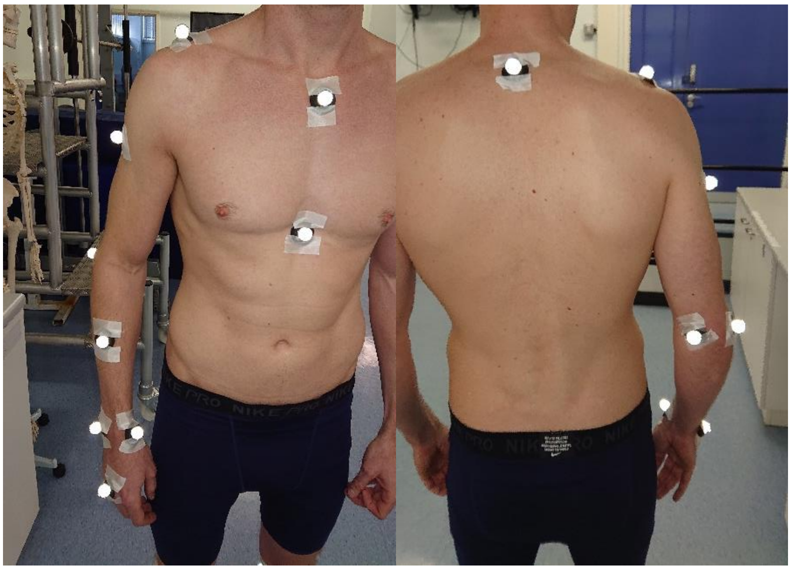

Figure 3-1: Marker placement used for data collection, anterior view (left) and posterior view (right).

The participant sat in a chair, positioned 3 m away from a curtain (Figure 3-2). A visual target (cross on the curtain, 30 cm x 30 cm) was placed directly in front of the participant at about eye level of the participant. Before collecting the data, the participant was allowed time to warm up by performing sub-maximal throws using the projectile. The throwing task consisted of a maximal overarm throw, restricted to the sagittal plane and movement of the arm segments only. This throwing motion, restricting movement to two dimensions, was chosen to be as close as possible to the two-dimensional simulation model. Kinematic data were obtained using eight infrared LED motion capture cameras recording at 150 Hz (Motion Analysis, Santa Rosa, USA).

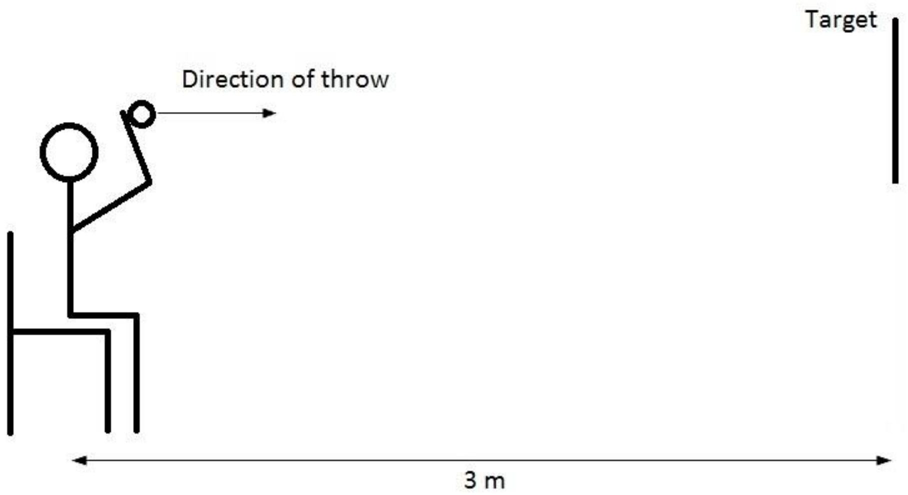

Figure 3-2: Diagram of the experimental setup. Participant throwing a ball towards a target positioned 3 m away. The participant was instructed to restrict his arm movement to the sagittal plane.

Due to the slightly unusual movement performed in this study and the requirement of minimal trunk movement, a relatively high number of throws (30) were recorded. The fastest throw with minimal trunk movement out of the recorded throws was used to calculate the joint torques. The raw marker position data were filtered using a low band-pass Butterworth filter with a cut-off frequency of 6.8 Hz. The cut-off frequency was obtained by performing a residual analysis of the marker's position data of the selected trial. An upper body model, consisting of the trunk segment and the right arm (Saul et al., 2014), was used in OpenSim 3.2 (Delp et al., 2007) in order to calculate the joint torques of both shoulder and elbow extension. OpenSim is an open-source software that allows users to create musculoskeletal models and simulate various dynamic movements (Delp et al., 2007). A third order polynomial curve was fitted to the time histories of the joint torques. The simulations were driven by a similar joint torque as was generated by the participant during the experiment.

3.2.3. Determination of subject-specific simulation characteristics

Experimental data were collected from a participant performing a two-dimensional throwing motion while sitting on a chair. The recorded throwing motion was used to calculate the participant's shoulder and elbow torques, and these torques were used as drivers for the simulation model. Additionally, the segment lengths of the model were chosen to be the measured arm segment lengths from the participant (Table 3-2), and the starting position of the simulation was set as the joint angles used by the participant before starting the throwing motion. The starting position for the simulated throws was a shoulder angle of 55˚ to the horizontal and an elbow angle of 55˚ (Figure 3-3). The mass, centre of mass, and moment of inertia of each segment was calculated using Dempster's data (1955). The mass of each segment was calculated as a fraction of the participant's total body mass (Upper arm: 0.0280; Forearm: 0.0160). The centre of mass of each segment was calculated as a fraction of the length of each segment from the proximal joint (Upper arm: 0.436; Forearm: 0.430).

Table 3-2: Segment characteristics of the 2D throwing model, obtained from the participant.

	Upper arm	Forearm
Segment length (m)	0.315	0.342
Distance of segment centre of mass from proximal joint (m)	0.137	0.147

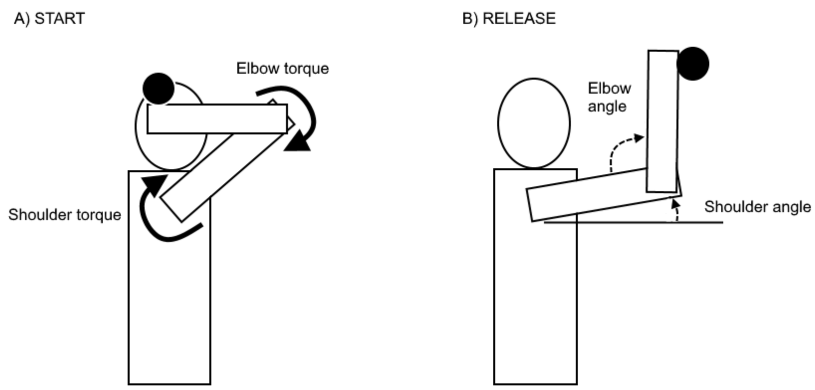

Figure 3-3: Two-dimensional throwing model with two degrees of freedom (shoulder and elbow joints).The figure shows the simulation A) at the start of the throw and B) at the instant of ball release.

3.2.4. Model description

The two-segment throwing model was created using Working Model 2D (Knowledge Revolution, San Mateo, CA). This software is an advanced two-dimensional motion simulation software which provides a graphical user interface to model real-world Newtonian mechanics and is mainly used to investigate engineering applications (Knowledge Revolution, 2006). The throwing model consisted of an upper arm segment, a forearm segment, and a ball (Figure 3-3). The lengths of the two arm segments were taken to be equal to those measured for the participant, and Dempster's (1955) data was used to calculate the location of the centre of mass and radius of gyration of the two segments. The upper arm segment is attached at the proximal end (shoulder) to the ground by a pin joint, and the forearm segment is attached to the distal end of the upper arm segment (elbow) by a pin joint. The starting position of the throw simulations was set to be the same as that used by the participant (Figure 3-3).

A ball with the dimensions of a tennis ball was fixed to the distal end of the forearm segment. The model is driven by joint torques at the shoulder and elbow joints. The magnitudes of the shoulder and elbow torques were obtained from experimental data recorded from a participant who performed a throwing motion that was restricted to arm movement in the sagittal plane. A rotational spring (stiffness = 2 N·m/˚) that simulates the passive structures around the shoulder was added at the shoulder joint to keep the joint angles within anatomical limits (Herring & Chapman, 1992). The magnitude of the rotational spring stiffness was determined by comparing the shoulder range of motion in the simulated throw to the experimental throw.

Even though humans do not normally use such a throwing technique to achieve high ball release speeds, this simplified two-dimensional throwing model was expected to provide general information about the effect of segment mass on performance in a kinetic chain. Although the degrees of freedom are reduced in this model, the sequential nature of maximum segment angular velocities of a throwing motion is retained. The upper arm mass was changed from 0.5 kg to 10 kg in increments of 0.5 kg, and the forearm mass was changed from 0.5 kg to 2 kg in increments of 0.1 kg, resulting in 320 simulated throws. I decided to simulate throws with a large range of upper arm and forearm masses in order to ensure that an optimum upper arm mass and forearm mass could be determined.

The release condition for all simulated throws was when the elbow angle reached 92° (180° elbow angle being at full elbow extension), which was the elbow angle used for the throw by the participant. A similar elbow angle at ball release was reported for a study analysing the accurate timing of ball release in a similarly restricted throwing motion (Hore, Watts, & Tweed, 1996). The throwing motion was simulated using five shoulder torque conditions: 1) torque obtained from the experimental data, 2) torque increased by 10%, 3) torque increased by 20%, 4) torque decreased by 10%, and 5) torque decreased by 20%. This resulted in a total of 1600 simulated throws (five torque conditions, each with 20 values of upper arm mass and 16 values of forearm mass).

A third order polynomial function was fitted to the experimental shoulder and elbow torque time histories (Figure 3-4). Four additional shoulder torque conditions were created by adding and deducting 10% and 20% to the experimentally obtained shoulder torque. A third order polynomial function was fitted to these data points, resulting in five shoulder torque conditions

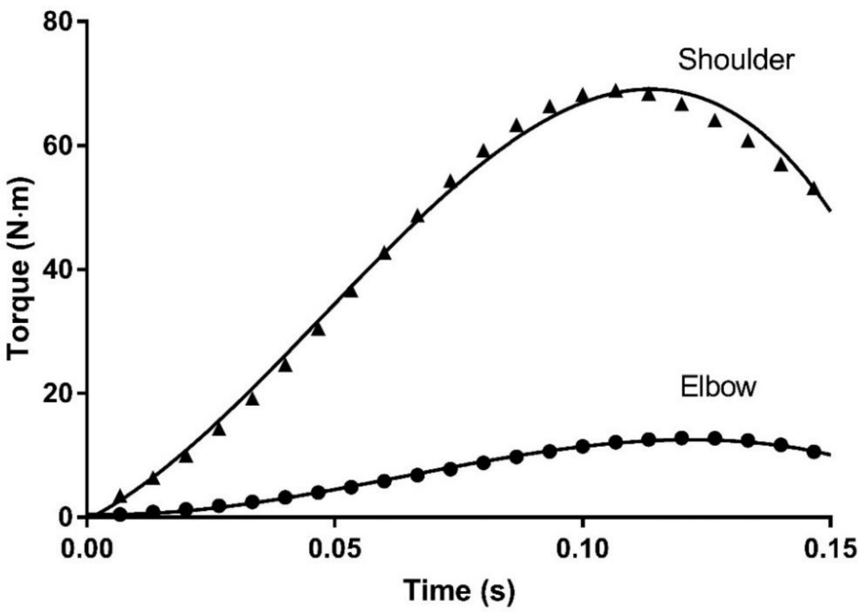

Figure 3-4: Time trace of the shoulder and elbow torque of the participant. The ▲ and ● represent the experimental data and the lines represent the third order polynomial curve fitted to the data that was used to drive the throwing simulations.

3.2.5. Dependent variables

The resultant ball release speed was obtained for each simulated throw at the time when the elbow angle reached 92˚. In addition to the ball release speed, the timing between the maximum upper arm angular velocity and the maximum forearm angular velocity were analysed. The timing was calculated relative to the total time of each individual throwing simulation, where the starting position was set at 0% and ball release at 100% of the throwing motion, similar to how previous research analysed throwing motions (Fleisig et al., 1996).

3.3. Results

The results of the two-dimensional two segment simulations performed in the present study highlight that there is an optimal upper arm mass that results in the highest ball release speed. Additionally, the ball release speed decreases as the forearm mass increases. During the throws performed with optimal upper arm mass, the maximum upper arm angular velocity occurred later compared to the throws performed with the arm segment masses of the participant tested for the present study. Furthermore, the optimal upper arm mass increases as the thrower's forearm mass increases.

3.3.1. Forearm mass

Increasing the forearm mass in the 2D throwing simulation resulted in a lower ball release speed (Figure 3-5). The ball release speed decreased as the forearm mass got heavier, independent of the amount of shoulder torque used to drive the simulation. This decrease in resultant ball release speed was observed for all upper arm masses. The highest ball release speeds were achieved with the lowest forearm masses. Further reducing the forearm mass beyond of the minimum used in this study would probably have resulted in even higher ball release speeds. On average, decreasing the forearm mass by 0.1 kg decreased the ball release speed by about 2.4%.

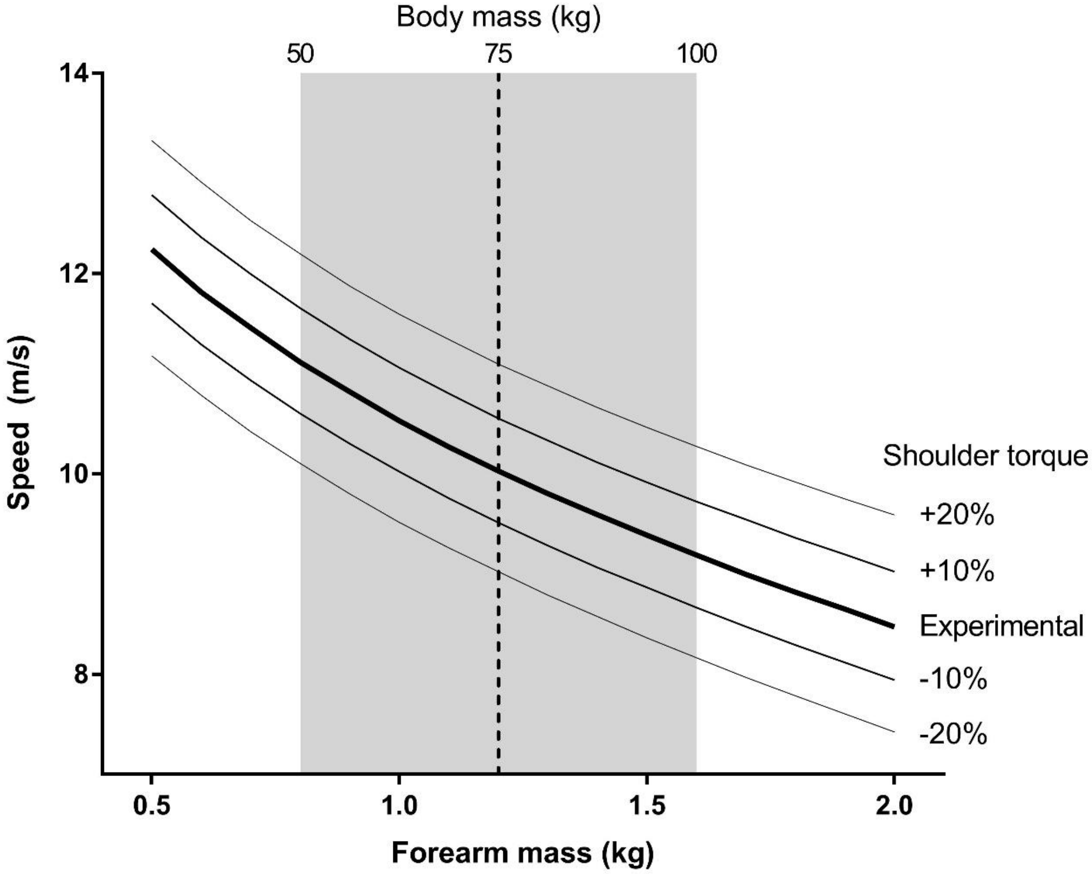

Figure 3-5: Effect of forearm mass and shoulder torque on ball release velocity. Ball release speed decreases with heavier forearm mass in all five torque conditions. Simulations are for an upper arm mass of an average adult male (2.0 kg). The shaded area represents the range of forearm masses expected for an adult male weighing between 50 kg and 100 kg.

3.3.2. Upper arm mass

Changing the upper arm mass in this simulation highlighted that there is an optimal upper arm mass that produces the greatest ball release speed (Figure 3-6). Optimising the upper arm mass for the throws performed with the experimentally recorded shoulder torque resulted in an increase of 0.60 m/s (5.9%). The optimal upper arm mass was 6.0 kg for the throws performed with the shoulder torque produced by the participant and less shoulder torque. Increasing the shoulder torque by 10% and 20% resulted in an optimal upper arm mass of 5.5 kg and 5.0 kg respectively. These optimal upper arm masses are around three times higher than the upper arm mass of an adult male. The results suggest that increasing the shoulder torque reduces the optimal upper arm mass.

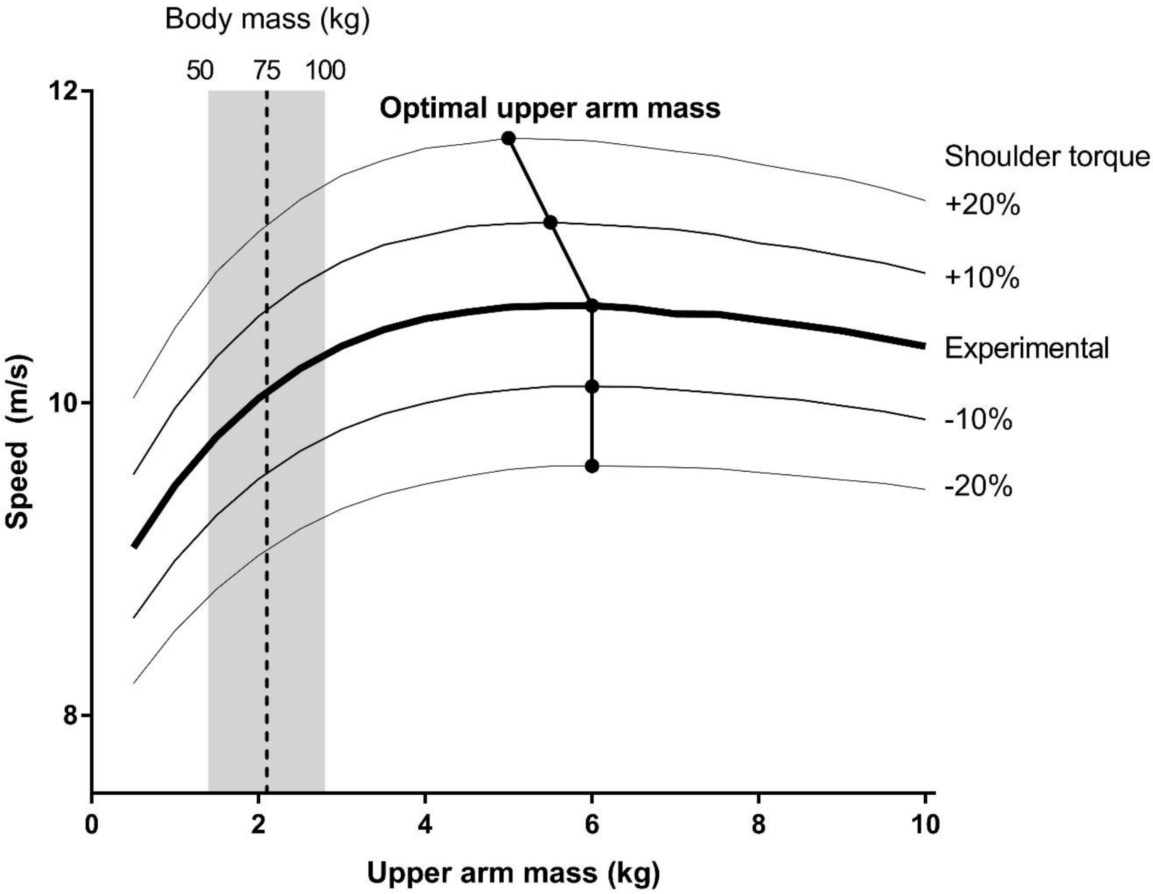

Figure 3-6: Effect of upper arm mass and shoulder torque on ball release speed. An optimal upper arm mass exists that results in the highest ball release velocity. The optimal upper arm mass is lower for the higher shoulder torque conditions. The simulations are for a forearm mass of an average adult male (1.2 kg). The shaded area represents the range of upper arm masses expected for an adult male weighing between 50 kg and 100 kg.

3.3.3. Optimum combinations of arm segment masses

The ball release speed reacted similarly for each shoulder torque condition (Figure 3-7). The highest ball release speeds were reached with an upper arm mass of 3.5 kg and a forearm mass of 0.5 kg. This optimal combination of arm segment masses was the same for each shoulder torque condition and resulted in an increase in ball release speed of about 2.5 m/s compared to the throws performed with the arm segment masses of the participant.

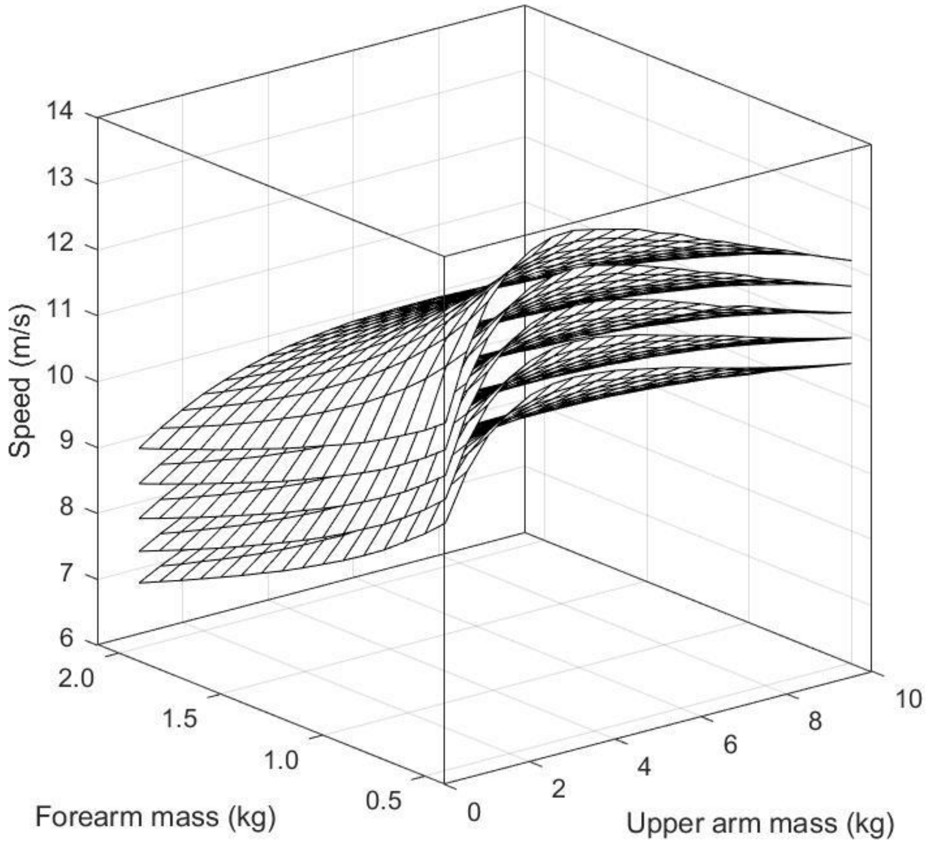

Figure 3-7: Effect of upper arm mass and forearm mass on ball release speed. Heavier forearm masses resulted in a decrease in ball release speed. For each forearm mass an optimal upper arm mass exists, which results in the highest ball release speed. Irrespective of the shoulder torque, an optimal upper arm mass exists, which depends on the forearm mass. Ball release speed for the five torque conditions are presented, with a 20% increase in shoulder torque resulting in the highest ball release speed and a reduction in shoulder torque by 20% in the lowest ball release speed.

The optimal upper arm mass increased as the forearm mass increased (Figure 3-8). The optimal upper arm mass is much higher than the upper arm mass of the participant. In order to determine the optimal relationship between the upper arm mass and the forearm mass, a straight line was fitted to the optimal upper arm mass reached with every forearm mass and for each torque condition. The results of the present study show that increasing the shoulder torque reduces the optimal upper arm mass for heavier forearm masses. The relationship between the optimal upper arm mass and the forearm mass for the throws simulated with the experimentally recorded shoulder torque is:

$$m_U = 3.248 \times m_F + 1.905$$

where m_U is the upper arm mass and m_F is the forearm mass.

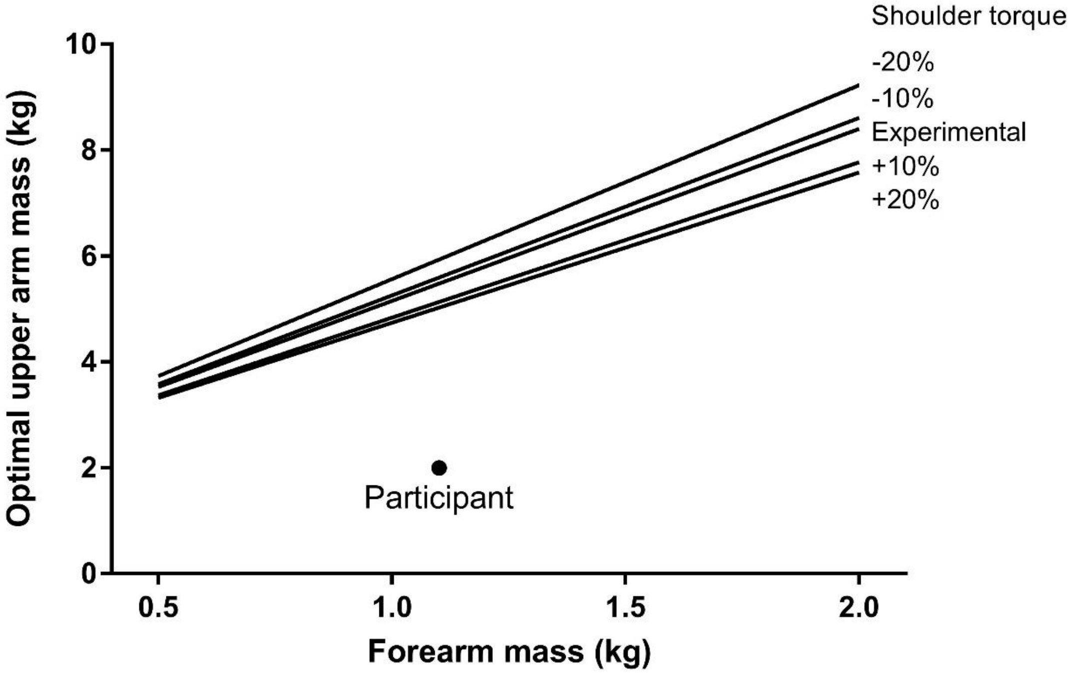

Figure 3-8: Optimal combination of arm segment masses. As the forearm mass increases the optimal upper arm mass also increases. The optimal upper arm mass is substantially greater than the upper arm mass of the participant or an average adult male. Increasing the shoulder torque slightly reduces the optimal upper arm mass.

3.3.4. Time of maximum segment angular velocities

The maximum elbow extension angular velocity always coincided with the time of ball release. During the throws simulated with the arm segment masses of the participant, maximum shoulder angular velocity occurred at about 72% for the different shoulder torque conditions. Throws simulated with the optimal upper arm mass for each forearm mass and shoulder torque condition reached the maximum shoulder angular velocity substantially later at about 80%. Optimising the upper arm mass in the simulated throws reduced the time that maximum elbow extension angular velocity lagged behind the maximum shoulder angular velocity.

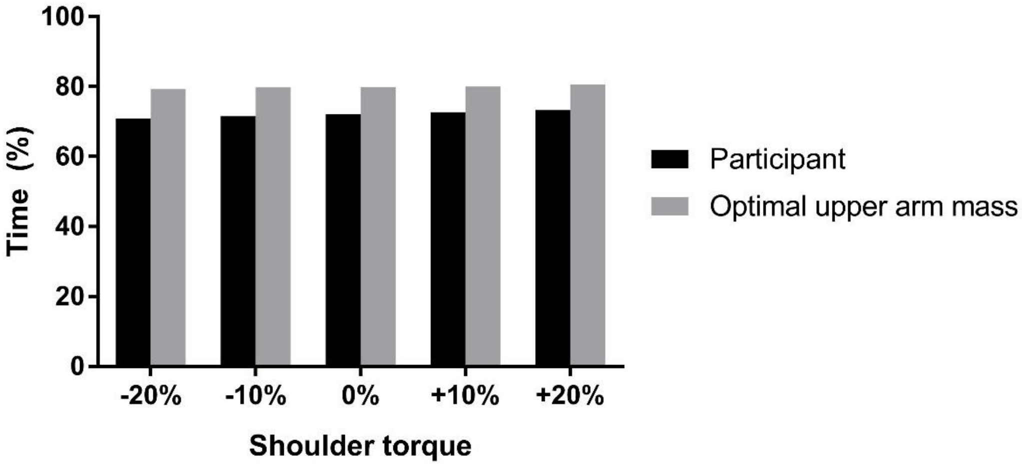

Figure 3-9: Maximum shoulder angular velocity occurred later in the throw for the throws simulated with the optimal upper arm mass (Mean across all five torque conditions: 80%) compared to the throws simulated with the arm segment mass distribution of the participant (Mean across all five torque conditions: 72%).

3.4. Discussion

The two-dimensional simulation of an overarm throw showed that for a given forearm mass there is an optimum upper arm mass which produces the highest ball release speed. However, the optimal upper arm is much higher than the upper arm mass of an average adult male. Increasing the forearm mass decreases the ball release speed, suggesting that athletes should attempt to keep their forearm as light as possible. The results also suggest that the optimal upper arm mass is lower in athletes that can generate higher shoulder torque. With the optimum combination of arm segment masses the maximum shoulder angular velocity occurs later during the throw.

3.4.1. Optimum combination of arm segment masses

In a kinetic chain the inertial parameters play a crucial role in creating fast and accurate movements. Throwing, which is amongst the fastest movements that a human can produce (Roach et al., 2013), relies heavily on the effective use of the kinetic chain to transfer angular momentum from one segment to the next and so produce a high ball release speed. The transfer of angular momentum increases the angular momentum of the distal segments as, in a human body, the distal segment (hand and forearm) is lighter than the proximal segment (upper arm) (Putnam, 1993; Winter, 2009). However, the results of the present study suggest that although the human anatomy allows us to throw a projectile fast and accurate, the upper arm mass of a typical adult human is substantially less than the optimal value. Additionally, keeping the forearm mass as low as possible increases the ball release speed.

3.4.1.1. Forearm mass

In the model used in the present study, reducing forearm mass from 1.0 kg to 0.5 kg increased ball release speed by about 1.7 m/s. Increasing the forearm mass, however, caused the ball release speed to decrease. The lowest forearm mass tested in this study was 0.5 kg, but the changes in ball release speed recorded for various amounts of forearm mass suggest that the ball release speed would further decrease with even lower forearm masses. However, a forearm mass of 0.5 kg is probably unrealistic for an athlete to reach. The findings from the present study suggest that throwing athletes should attempt to keep their forearm mass as low as possible, confirming the results of previous studies (Kim et al., 2008; Southard, 1998). Previous studies reported that both the elbow flexion/extension and wrist flexion/extension are mainly produced through velocity-dependant torques generated at more proximal joints (Hirashima et al., 2008), and that muscles crossing the wrist are predominantly responsible to control the accurate release (Hirashima et al., 2003). These findings combined with the results of the present study suggest that increasing the mass of the muscle groups running alongside the forearm and crossing the wrist joint could have a negative effect on throwing velocity.

3.4.1.2. Upper arm mass

The results of this study agree with previous studies (Kim et al., 2008; Southard, 1998) which found that a heavier upper arm can increase ball release speed. The present study showed that there is an optimal upper arm mass, which increases ball release speed by about 6%. However, a throwing athlete would have to nearly triple their upper arm mass in order to reach this optimum. Increasing the mass of the muscles in the upper arm would probably also result in an increase in muscle strength as well as an increase in upper arm mass. However, a substantial increase in muscle mass might reduce the flexibility at the shoulder joint, which might then affect the athlete's ability to throw fast and accurate. Therefore, further analysis is required in order to determine how upper arm mass influences the kinetic chain and throwing velocity in a full-body throwing motion.

Furthermore, the optimal upper arm mass of the two-dimensional simulation changes with different amounts of shoulder torque, suggesting that the optimal arm mass is lower in athletes that produce more shoulder torque. Therefore, the optimal upper arm mass of skilled throwers could be lower compared to less skilled throwers. Similar findings were observed in a study comparing the effect of upper arm mass on ball release speed between throwers of various skill levels (Southard, 1998), where only less skilled throwers benefited from additional upper arm mass. Combined with the higher muscle volumes on baseball pitchers' dominant upper arm (Yamada, Yamashita, et al., 2013), the results of the present study indicate that baseball pitchers might already be at their optimal upper arm mass through their training routine.

3.4.2. Temporal lag of joint rotations

Optimising the masses of the upper arm and the forearm results in the maximum angular velocity of the upper arm occurring later in the throwing motion. This temporal change in the throwing movement confirms the importance of the relative timing of the joint rotations during the proximal-to-distal sequence (Southard, 2009). The correct timing of joint rotations along the kinetic chain allows the throwing athlete to optimise the transfer of energy between the segments (Southard, 2009; Stodden et al., 2006), which in the present two-dimensional simulation was achieved through changes in arm segment mass.

3.4.3. Throwing projectile

In the present study, a tennis ball was used to be thrown as fast as possible. This fairly light projectile (58 g) was used in order to avoid injuries caused by the slightly unusual throwing motion recorded in the present study. As projectiles used by our ancestors (Isaac, 1987) and projectiles used in various sports (Bartlett, 2000) are heavier, the low mass of the tennis ball might have affected the results of the present study. The mass of the ball thrown might therefore be partly responsible for the high optimum upper arm mass determined in the present study. However, further analysis is required in order to determine how the mass of the projectile affects the optimal upper arm mass and if the masses of the different arm segments evolved to optimise the throwing of heavier objects than are used in sports today.

3.4.4. Limitations

In this study, a simplified throwing model was used to determine if there is an optimal combination of arm segment masses that results in the fastest ball release speed in overarm throwing. The model used only contains an upper arm and forearm segments and a shoulder and elbow joint. According to Hirashima (2002), the muscle torque at the wrist counteracts the interaction torque and thus the wrist joint does not contribute much towards ball release speed but is mainly responsible for the accurate ball release. Therefore, the omission of a wrist joint in the model should not affect the influence of arm segment mass on the ball release speed.

In the simple throwing model, the shoulder joint was represented as a pin joint and so the simulated throws did not include internal shoulder rotation, which is one of the major contributors to ball release speed in overarm throwing. Thus, the model used in this study was not able to identify the impact of internal shoulder rotation on the optimal combination of arm segment masses. In addition, the simulated throws did not include a wind-up and only focused on the forward movement of the arm segments and the ball. Optimising the arm segment masses could increase the elastic energy generated at the shoulder, because the upper arm lags further behind the trunk. Therefore, including a shoulder joint in a model of throwing that allows rotation around all axes could affect the optimal arm segment masses and, as a result, the improvements in throwing velocity observed in the present simulation.

Furthermore, the lack of subject-specific segmental inertial parameters constitutes another limitation. However, due to simplistic nature of the model used in the present study, it was assumed that using subject-specific segmental inertial parameters would not have a substantial effect on the outcome of the study.

Even though there are several limitations to the present throwing simulation, the two-dimensional model confirmed previous findings that additional upper arm mass improves throwing velocity. In addition, the results of the present study identified the optimal arm segment mass that results in the highest ball release speed. The present study is the first step in identifying the existence of an optimal arm segment mass distribution that maximises the ball release speed and thus highlights the importance of using this concept in order to improve an athlete’s ability to throw a projectile.

3.4.5. Applications

The present study confirms the findings of previous studies that found that a heavier upper arm can increase throwing velocity (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). The present study extends our knowledge by highlighting that athletes attempting to throw as fast as possible can optimise their arm segment masses. Thus, throwing athletes and their coaches could be advised to monitor the athlete’s arm segment masses in order to benefit from this effect. Hypertrophy training could be included into an athlete’s training routine to maximise the effect of anthropometrics on their throwing velocity. However, hypertrophy training might also change muscle strength, and this might affect the throwing velocity.

3.4.6. Further Work

Even though this study confirmed that there is an optimal combination of arm segment masses in an overarm throw in the sagittal plane, we do not known what the optimal masses are in a more realistic overarm throwing motion. Due to the limitations of the simplified model used in this study, further work is required in order to determine if athletes in throwing sports could benefit from optimising their arm segment masses. Previous studies have identified that increasing the upper arm mass results in a faster ball release speed (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), but none of the studies analysed the existence of an optimal upper arm mass in a throwing motion with the aim to maximise ball release speed. Analysing the ball release speed of throws performed with various amounts of mass attached to a thrower’s upper arm could lead to identifying the optimal upper arm mass for athletes attempting to throw as fast as possible.

Additionally, no study has investigated the effect that additional upper arm mass has on an athlete's throwing technique. Due to the two-dimensional nature of the model used in this study, the movement at the shoulder joint was restricted to a pin joint, ignoring some crucial rotations in generating high ball release speeds (Fleisig et al., 1999; Hirashima et al., 2008). Analysing both kinematic and kinetic variables that have previously been identified as significantly contributing to high ball release speeds could lead to understanding how a heavier upper arm mass results in an increase in performance and determine if it increases the risk of injuries.

Previous research suggests that the optimal upper arm mass could be subject-specific and depend on the person's forearm mass (Linthorne et al., n.d.). The model used in this study confirmed the relationship between the forearm mass and the optimal upper arm mass. Due to the simplified shoulder rotation and the restrictions of the movement to two dimensions, a more complex model would be required in order to accurately predict an athlete's optimal upper arm mass. Therefore, further research is required to develop a more realistic computer model that can be used by coaches in order to simulate an athlete's throwing performance.

3.5. Conclusions

This study confirms that the inertial parameters of the arm segments can affect throwing performance. Although the results were obtained using a simplified model of an overarm throwing motion, the study extends our knowledge of the importance of segment mass in the kinetic chain. The most important finding of this study is that there is an optimal upper arm mass for this two-dimensional throwing simulation. Furthermore, a heavier forearm mass has a negative effect on throwing velocity. As a result, the optimal upper arm mass and the optimal forearm mass in the two-dimensional throws simulated in the present study are probably unrealistic for humans to achieve. However, the lower optimal upper arm mass for the throws simulated with a higher amount of shoulder torque indicates that the optimal upper arm mass of skilled throwers might be lower than the optimal upper arm masses observed in the present study.

Chapter 4: Kinematic and kinetic analysis of additional upper arm mass in overarm throwing.

4.1. Introduction

The ability to throw both fast and accurate is a skill that is unique to humans (Young, 2009). The main reason for a human's ability to throw a projectile is the anatomy of our body. Two anatomical characteristics that set us apart from other species are our tall, mobile trunk and our flexibility at the shoulder joint. These characteristics allow the energy produced at the trunk to be stored at the shoulder and transferred to the arm and the projectile (Roach & Richmond, 2015a; Roach et al., 2013). Furthermore, this transfer of energy and angular momentum is enhanced by the mass distribution of the segments along the kinetic chain (Stodden, Fleisig, McLean, Lyman, & Andrews, 2001) as the distal segments are lighter compared to their proximal neighbour segments (de Leva, 1996). The anthropometric characteristics of the human body allow skilled throwers to increase the angular velocity of the distal segments due to conservation of angular momentum (Putnam, 1993), resulting in high ball release speeds. The ability of humans to throw projectiles was an evolutionary adaptation to hunt for prey and defend against enemies (Young, 2009), and throwing is still performed today in sports such as baseball, cricket, and some of the field events in athletics. The goal in these sporting events is to maximise throwing performance by either throwing the projectile faster or farther.

Previous studies have shown that anthropometric parameters can affect throwing performance. A study comparing high and low velocity baseball pitchers found significantly longer arm segment lengths in the high velocity group (Matsuo et al., 2001). However, as it is not possible to change the segment lengths of an athlete, some research has focused on adapting the arm segment masses in order to improve throwing performance (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). Changes in segment mass can be achieved through muscle hypertrophy training.

4.1.1. Inertial parameters in throwing

Previous studies found that changes in mass distribution of the throwing arm affect ball release speed. An increase by around 6.4% in ball release speed was observed with additional mass (average: 1.4 kg) attached to the upper arm (Southard, 1998). The results of this study indicate that less skilled throwers improved the use of the kinetic chain with additional upper arm mass, thus increasing their ball release speed. Another study measured a slight increase in horizontal arm swing velocity with 25% and 50% increase in upper arm mass (Kim et al., 2008). A study focussing on the performance of javelin throwers observed that the optimal upper arm mass for both release velocity and distance thrown is higher than their actual upper arm mass (Linthorne et al., n.d.). The optimal upper arm mass in this study depended on the participant and resulted in an average increase in throw distance of 5.4%. These findings are similar to those obtained from the two-dimensional simulation performed in Chapter 3, where an optimal upper arm mass results in the highest ball release speed. The optimal upper arm mass in the two-dimensional simulation study is more than double the upper arm mass of an average adult male.

Additionally, a study that restricted the wrist motion in overhand throwing found a decrease in ball velocity (Roach & Lieberman, 2014). However, instead of relating the decrease in ball velocity to the restricted movement, the investigators concluded that the increase in mass at the distal end of the kinetic chain was responsible for the decrease in velocity. The mass of the wrist brace resulted in a decrease in maximum internal shoulder velocity, but did not significantly affect the elbow extension velocity. Further evidence on the negative effect that a heavier forearm mass has on throwing performance was provided by studies analysing maximum throws (Southard, 1998), horizontal arm swing velocity (Kim et al., 2008), and two-dimensional simulations of overhead throwing (Chapter 3).

Although some studies showed that a heavier upper arm mass can have a positive effect on the ball release speed and throwing distance of a projectile, no previous study managed to detect the optimal upper arm mass that maximises the ball release speed, as was discovered in my previous study using two-dimensional simulations (Chapter 3). Only a study by (Linthorne et al., n.d.) identified the optimal upper arm mass for three javelin throwers to be between 0.21 kg to 0.60 kg heavier than their actual upper arm mass. Additionally, little is known about how changes in upper arm mass affect the kinematics and kinetics of throwing. Understanding how upper arm mass affects an athlete’s throwing technique could help to determine an athlete’s optimal upper arm mass and reveal if athletes can safely apply this principle without increasing the risk of injury.

4.1.2. Kinematics of throwing performance

In addition to the anatomical characteristics of the human body, several kinematic variables have been identified as major contributors to high ball release speeds. However, only limited research is available that analysed kinematic changes with additional upper arm mass. Southard (1998) reported faster arm segment linear velocity for the condition with additional upper arm mass compared to throws performed with additional mass attached to other arm segments. Even though previous studies detected an increase in ball release speed with additional upper arm mass (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), none of these studies analysed the effect the additional mass has on joint kinematic variables that have previously been identified to assist the generation of high ball release speeds. As the main objective of the throws performed during the present study was to throw as fast as possible, while attempting to hit a target, the following sections will focus on the kinematics of baseball pitching.

4.1.2.1. Legs

The generation of high ball release speed starts with the legs and the trunk, which serve as a stable base for the ballistic motion of the upper arm (Seroyer et al., 2010), which is highlighted by the importance of the stride length. In baseball pitching the stride length is between 74% and 87% of the participant's body height (Fleisig et al., 1996; Matsuo et al., 2001). Although the stride length did not vary between different ball velocity groups (Matsuo et al., 2001), decreasing the stride length to around 50% of body height resulted in the upper arm lagging further behind the trunk rotations compared to longer stride lengths (Ramsey & Crotin, 2016; Ramsey et al., 2014), potentially increasing the risk of injury (Aguinaldo et al., 2007).

Both stride knee flexion angle and angular velocity play a crucial role in throwing performance. A multiple linear regression analysis identified the knee angle of the lead leg at the instants of lead foot contact and at ball release to affect ball release speed (Werner et al., 2008). Baseball pitchers throw with a more flexed lead knee at both instants compared to American football passing (Fleisig et al., 1996) and reach values of 51 ± 11° at the instant of foot contact and 40 ± 12° at the instant of ball release. Similar values were recorded in a study comparing baseball pitchers of various levels of development (Fleisig et al., 1999). Lead knee extension angular velocity at the instant of ball release is significantly higher for pitchers that achieve higher ball release speeds (Matsuo et al., 2001).

4.1.2.2. Trunk

Forward trunk tilt at the instant of ball release is related to high ball release speed (Dowling et al., 2016; Fortenbaugh et al., 2009; Seroyer et al., 2010; Werner et al., 2008). A larger forward trunk tilt angle has been recorded in a high velocity (37 ± 7°) baseball pitching group compared to a low velocity (29 ± 11°) group (Matsuo et al., 2001). Increasing the forward tilt angle towards ball release permits a baseball pitcher to accelerate their throwing arm over a longer distance and thus perform more work on the ball (Seroyer et al., 2010; Stodden et al., 2005). Additionally, the maximum trunk angular velocity is higher in professional baseball pitchers compared to their less experienced counterparts (Fleisig et al., 1999), while another study observed a correlation between higher trunk angular velocities and higher ball release speeds (Dowling et al., 2016).

4.1.2.3. Shoulder

The shoulder joint plays a crucial role in overhead throwing due to its flexibility (Veeger & van der Helm, 2007) and ability to store elastic energy which supports the generation of high angular velocities of the distal segments (Roach et al., 2013). Especially the maximum external shoulder rotation angle has previously been linked to contribute to high ball release speeds, reaching angles of external rotation of around 180° (Dun et al., 2007; Fleisig et al., 1996, 1999; Sabick, Torry, Kim, et al., 2004; Stodden et al., 2005; Werner et al., 2008). A pitcher who is able to produce more external shoulder rotation, due to low humeral torsion (Roach et al., 2012; Roach & Richmond, 2015b), can generate a higher ball release speed (Matsuo et al., 2001).

However, an increase in maximum external shoulder rotation does not necessarily result in an increase in internal shoulder rotation angular velocity (Matsuo et al., 2001). Although, an increase in external shoulder rotation allows the ball to be accelerated over a greater distance (Seroyer et al., 2010). Furthermore, some studies have associated higher ball release speeds with higher internal shoulder rotation angular velocities (Fleisig et al., 1999; Werner et al., 2008). Some studies have recorded internal shoulder rotation angular velocities in baseball pitchers surpassing 10,000°/s (Werner et al., 2001).

Additionally, the shoulder abduction angle during the arm acceleration phase affects ball release speed (Stodden et al., 2005). A study using a three segment computer simulation of the throwing arm identified that the optimal shoulder abduction angle is around 90° in order to maximise wrist velocity (Matsuo et al., 2002).

4.1.2.4. Elbow

Elbow flexion angle at the instant of stride foot contact and at the instant of ball release have previously been associated with high ball release speeds (Stodden et al., 2005; Werner et al., 2008). In preparation for the arm cocking phase, the elbow of skilled throwers is flexed to around 90° in order to increase the moment of inertia around the longitudinal shoulder rotation axis, allowing the generation of larger external shoulder rotation angles (Stodden et al., 2006). After maximum external shoulder rotation is reached, the elbow rapidly extends with angular velocities of around 2300°/s (Dun et al., 2007; Fleisig et al., 1999) to 2500°/s (Werner et al., 2001), which allow athletes to reach elbow flexion angles of around 25° at the instant of ball release (Stodden et al., 2005).

4.1.3. Temporal characteristics of throwing performance

High ball release speeds are reached through sequential proximal-to-distal segment movements, as the distal segment reaches a higher velocity compared to their proximal neighbour through conservation of angular momentum (Putnam, 1993). However, not only the correct sequence is important in overhead throwing, but also the relative timing of certain key events throughout the motion (Southard, 2009). Several temporal parameters are correlated with higher ball release speeds. In order to compare the timing between throws, most studies report temporal parameters as a percentage of the throwing motion (0% is stride foot contact; 100% is instant of ball release). A group of high velocity baseball pitchers reached maximum elbow extension angular velocity earlier (91.1% ± 1.9%) compared to a low velocity group (93.0% ± 2.4%) (Matsuo et al., 2001). Similar findings are obtained for the time of maximum internal shoulder rotation, which occurs closer to the instant of ball release for the high velocity group (102.3% ± 2.0%) compared to the low velocity group (104.4% ± 1.8%) (Matsuo et al., 2001). Another study also detected an increase in trunk separation time, meaning the time between maximum pelvis angular velocity and maximum trunk angular velocity, as the ball velocity increased (van der Graaff et al., 2016).

Attaching additional mass to the upper arm mass affects the timing between maximum segment angular velocities. Southard (1998) reported that less skilled throwers who did not produce a proximal-to-distal sequence of maximum segment angular velocities managed to improve their kinetic chain with a heavier upper arm mass, which enables them to increase their ball release speed. However, additional upper arm mass did not affect the skilled throwers in this study. Additionally, in my previous study (Chapter 3) the throws simulated with the optimal upper arm mass occurred after around 80% of the whole throwing motion, which is later compared to the throws simulated with the upper arm mass of an average adult male (at around 70% to 73% of the total throwing time). These findings confirm that optimal upper arm mass can result in temporal changes of an athlete's throwing technique.

4.1.4. Kinematic and kinetic variables related to injuries

Apart from increasing performance, another objective of a biomechanical analysis is to reduce the risk of injury by optimising technique and as a result decrease the loads on the joints. Due to the rapid nature of the throwing motion, high joint torques and joint forces are produced throughout the movement, which can result in injury, especially to the shoulder or the elbow joint (Conte et al., 2001). Improving an athlete's throwing technique can result in both an increase in throwing performance and a reduced risk of injury by optimizing the use of the kinetic chain and decreasing the stress on the joints (Seroyer et al., 2010).

According to Newton's second law of motion ($F = m \cdot a$), an increase in either the acceleration or the mass results in an increase in the force that needs to be applied. Therefore, an increase in upper arm mass should lead to higher forces and as a result higher stresses, especially on the shoulder joint. However, this simple theory becomes much more complex due to the temporal sequencing of the kinetic chain in overhead throwing (Fortenbaugh et al., 2009). Through improving the mechanical efficiency of the throws, skilled throwers cause less stress on their joints while increasing the ball release speed (Fortenbaugh & Fleisig, 2009). Therefore, the success of attaching additional mass to the participant's upper arm cannot only be measured by an increase in ball release speed, but also by the joint forces and joint torques acting on the throwing arm.

Overuse injuries in throwing result from high forces and torques that act mainly on the shoulder and elbow joints (Fortenbaugh et al., 2009). Several studies have reported forces and torques acting on the shoulder and elbow joints and related them to various kinematic variables that affect the generation of high stresses (Buffi et al., 2015; Fleisig et al., 1995; Werner et al., 2001, 2002). Shoulder compression force and elbow valgus torque in particular have been identified as leading to injuries in sports such as baseball (Werner et al., 2001, 2002). Shoulder compression force reaches values of around 1090 ± 110 N in highly skilled baseball pitchers (Fleisig et al., 1995) or around 108 ± 16% of a professional baseball pitcher's body weight (Werner et al., 2001). Even though the maximum compression force in collegiate baseball pitchers is significantly lower (81 ± 10% of body weight), it is still regarded as a major risk for injury (Werner et al., 2008).

In professional baseball pitchers, shoulder compression force is related to a higher maximum shoulder external rotation angle, a higher shoulder internal rotation and shoulder abduction torque, and the elbow flexion angle both at the instant of ball release and at the instant of stride foot contact (Werner et al., 2001). Improper maximum shoulder external rotation, which reach angles between 158° and 185° (Aguinaldo & Chambers, 2009; Fleisig et al., 2006; Werner et al., 1993, 2008) has been identified to cause high loads on the shoulder joint. An increase in shoulder internal rotation torque has also been observed with an early onset of trunk rotation, which leads to greater stress on the shoulder joint (Aguinaldo et al., 2007).

Maximum elbow valgus torques during the arm cocking phase reaches 120 N·m (Werner et al., 1993). Similar to the maximum compression force at the shoulder, the maximum valgus torque is also affected by the maximum external shoulder rotation and the elbow flexion angle at the instant of maximum valgus torque (Aguinaldo & Chambers, 2009). In addition, higher elbow valgus torques have also been measured with improper shoulder abduction angles using a three segment model to run three dimensional simulations (Matsuo et al., 2002).

Optimising the upper arm mass could lead to an optimisation of the kinetic chain of throwing, resulting in an increase in throwing performance while not increasing the stresses on the both the shoulder and the elbow joint. In the present study, kinematic and kinetic variables that have previously been identified to affect the risk of injuries will be analysed in order to determine if this method is suitable for athletes and coaches to adopt. Especially the shoulder compression force, the elbow valgus torque, internal shoulder torque have been recognised as the main kinetic variables causing overuse injuries in baseball pitching (Chalmers et al., 2017;

Fortenbaugh et al., 2009; Seroyer et al., 2010). Kinematic variables that lead to higher stresses are the maximum external shoulder rotation, elbow flexion angle throughout the throwing motion, and timing of trunk rotation (Aguinaldo et al., 2007; Aguinaldo & Chambers, 2009; Werner et al., 2001).

4.1.5. Aims of the study

The main aim of the present study was to identify the optimal upper arm mass in overarm throwing which produces the highest ball release speed. Even though previous studies have identified that a heavier upper arm mass can improve an athlete’s throwing performance (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), none of these studies attempted to determine the optimal upper arm mass in a throwing task with the goal of maximising the ball release speed. The throws analysed in the present study are similar to throws performed by baseball pitchers.

Furthermore, the present study analysed how additional upper arm mass affects an athlete’s throwing technique and what effect additional upper arm mass has on the risk of injury. No previous study has analysed how additional upper arm mass affects joint angular kinematics and kinetics. Determining the optimal upper arm mass in maximal-effort overarm throwing and identifying how changes in upper arm mass affect throwing technique will provide further insight into how athletes could benefit from optimising their upper arm mass. Additionally, analysis of variables related to both shoulder and elbow injuries in baseball pitching will highlight if coaches should attempt to apply this method.

4.1.6. Hypotheses

The following hypotheses were tested in the present study:

- Optimising the mass of the upper arm results in a substantially higher ball release speed.
- Changes in upper arm mass do not affect maximum joint angles, joint angles at the instant of lead foot contact, joint angles at the instant of ball release, and joint angular velocities.
- Changes in upper arm mass affect the timing of maximum joint angles and timing of maximum joint angular velocities
- Heavier upper arm mass increases joint torques and joint forces.

4.2. Methods

The present study used an experimental approach. The participants performed maximal throws using a baseball with masses attached to their upper arm. Motion analysis data of the throws were recorded in order to analyse kinematic, kinetic, and temporal variables that have previously been identified to either relate to throwing performance (Fleisig et al., 1996; Matsuo et al., 2001) or injury prevention (Fortenbaugh et al., 2009; Seroyer et al., 2010) in baseball pitching. Analysing how additional upper arm mass affects ball release speed as well as joint kinematics and kinetics provides evidence about how an athlete’s throwing technique is affected by changes in upper arm mass. Ethics approval was obtained from the College of Health and Life Sciences at Brunel University London.

4.2.1. Participants

Thirteen healthy adults (7 male, 6 female) participated in the study (Table 4-1). After agreeing to take part, all participants signed an informed consent form. All participants were physically active, but none regularly practiced a sport where throwing a projectile as fast as possible was required (eg. baseball, cricket, javelin throw). None of the participants reported having a shoulder injury in the six months prior to testing. The location of the centre of mass of the upper arm was calculated as a percentage of the length of the upper arm, and the mass of the upper arm was calculated as a percentage of the total body mass (de Leva, 1996).

Table 4-1: Characteristics of the participants (mean, SD). n=13

Participant	Gender	Height (cm)	Mass (kg)	Upper arm length (cm)	Calculated upper arm mass (kg)
1	Male	178	82	31	2.2
2	Male	172	76	31	2.1
3	Male	187	77	32	2.1
4	Male	177	65	30	1.8
5	Male	174	71	30	1.9
6	Male	182	69	30	1.9
7	Female	158	54	28	1.4
8	Female	171	55	29	1.4
9	Female	164	58	29	1.5
10	Female	161	71	28	1.8
11	Female	160	63	27	1.6
12	Female	168	65	27	1.7
13	Male	183	78	32	2.1
Mean		172.2 ± 9.1	69.0 ± 9.3	29.6 ± 1.8	1.8 ± 0.3

4.2.2. Data collection

Data collection took place in the Biomechanics Laboratory at Brunel University London. In addition to the participant's body height and body mass, the length of their upper arm was measured at the beginning of the testing session in order to determine the location of the centre of mass of their upper arm, which was calculated as a percentage of the upper arm length (de Leva, 1996). Additionally, the participant's upper arm mass was determined as a percentage of their total body mass; 2.55% for female participants and 2.71% for male participants (de Leva, 1996). The additional amount of mass was specific to the participant and was calculated as a percentage of his or her upper arm mass.

Each participant completed a total of 30 maximal-effort throws with various amounts of mass attached around the centre of mass of their throwing arm. Apart from throws performed without additional mass, the participant's upper arm mass was increased by 10%, 20%, 30%, 40% and 50% of body mass. The average mass attached to the upper arm for each condition was 0.18 kg ± 0.03 kg, 0.37 kg ± 0.06 kg, 0.55 kg ± 0.09 kg, 0.73 kg ± 0.12, and 0.91 kg ± 0.14 kg respectively. The masses attached to the participant's upper arm ranged between 0.14 kg and 1.12 kg. The additional mass consisted of lead shot and was attached to the participant's upper arm with Vet-Wrap (a cohesive bandage). The additional mass was attached evenly around the centre of mass of the upper arm. Care was taken while attaching the masses in order to ensure that the participant's throwing motion was not restricted or hindered. Five throws for each upper arm mass condition were recorded.

At the start of the testing session, 46 reflective markers were placed on anatomical landmarks of the participant's body and the body segments in order to calculate joint rotations (Table 4-2, Figure 4-1, Figure 4-2). Two reflective markers were placed on the ball in order to calculate the ball release speed. Motion analysis data were recorded of the throws using 10 infrared LED cameras (Motion Analysis, Santa Rosa, USA) at 150 Hz. The participant threw a baseball ball (148 g) as fast as possible towards a target positioned 5 m in front of them. The target was a cross marked on a curtain at the height of the participant's shoulder (30 cm x 30 cm). The accuracy of the throws was not measured, but all throws hit the curtain.

Table 4-2: Placement of the markers on the anatomical landmarks and the body segments of the participants. 46 reflective markers were placed on the participants.

Markers on the anatomical landmarks	Markers on the body segments
Sternum*	Upper arm
Xiphoid process*	Forearm
C7*	Thigh
Acromion	Shank
Lesser tuberosity	Back*
Lateral epicondyle	
Medial epicondyle	
Styloid process of ulna	
Styloid process of radius	
3rd metacarpophalangeal joint	
Anterior superior iliac spine (ASIS)	
Posterior superior iliac spine (PSIS)	
Greater trochanter	
Lateral femoral condyle	
Medial femoral condyle	
Lateral malleolus	
Medial malleolus	
1st metatarsal	
5th metatarsal	
Calcaneus	

*Only one marker; all other markers were placed on the right and left side of the body

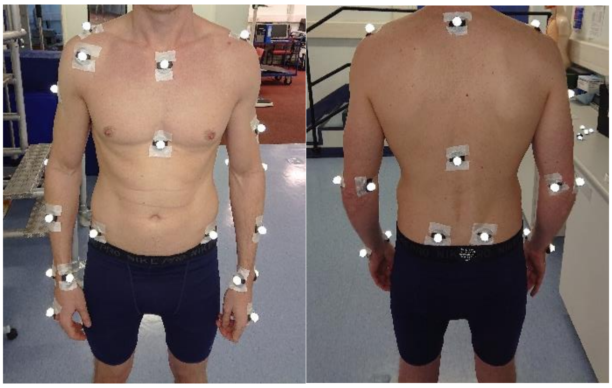

Figure 4-1: Marker set on the upper body, anterior view (left) and posterior view (right).

Figure 4-2: Marker set on the lower body, anterior view (left) and posterior view (right).

Before the throws were recorded, the participant was allowed to perform their individual warm-up and stretching in order to avoid injuries (Oliver, Plummer, & Keeley, 2011). Additionally, before each mass condition, the participant was allowed enough time to become familiar with the new task in order to avoid any learning effect during the recorded throws (Hopkins, 2000). The participant performed five throws for each upper arm mass with the only instructions given to throw as fast as possible. No further instructions were given to the participants in relation to their technique and they did not receive any feedback about their technique or their performance throughout the session (Štirn, Carruthers, Šibila, & Pori, 2017). The order of the mass conditions was randomised between the participants in order to avoid order effects on the results of the study.

4.2.3. Data analysis

The data from this study were analysed using Visual 3D software (C-Motion, Inc., Rockville, MD, USA) to quantify kinematic, kinetic, and temporal variables of the overarm throws with additional upper arm mass.

4.2.3.1. Model characteristics

The present study used a three-dimensional model consisting of 12 segments representing the trunk, the dominant arm, and the legs (Table 4-3 and Figure 4-3). The characteristics of the trunk and the arm were similar to those used in previous studies that used the same software (Roach & Lieberman, 2014; Roach et al., 2013). In addition to the trunk and dominant arm, the model included a pelvis segment and the two legs in order to measure stride length and the knee angle of the lead leg. The characteristics of each segment such as segment mass, moment of inertia, and segment centre of mass were those used by de Leva (1996). The upper arm mass and the moment of inertia were adjusted in the model for the different mass conditions. The moment of inertia of the upper arm segment was adjusted around all three axes using the formula:

$$Moment\ of\ inertia = Segment\ mass * (Radius\ of\ gyration * Segment\ length)^2$$

Table 4-3: Segment definitions and order of joint rotations of the Visual 3D model.

Segment	Proximal Markers	Distal Markers	Axes (order of rotations)
Pelvis	Right ASIS Left ASIS	Right PSIS Left PSIS	
Thorax	Right Acromion Left Acromion	Right ASIS Left ASIS	Z: tilt forward/backward X: tilt sideways Y: axial rotation
Upper arm	Shoulder JC (calc)	Elbow lateral Elbow medial	Y: horizontal ab/adduction X: ab/adduction Y: int/external rotation
Forearm	Elbow lateral Elbow medial	Wrist lateral Wrist medial	Z: flexion/extension
Hand	Wrist lateral Wrist medial	Metacarpal 3	Z: flexion/extension X: ulnar/radial deviation
Thigh	Hip JC (calc)	Knee lateral Knee medial	
Shank	Knee lateral Knee medial	Ankle lateral Ankle medial	Z: flexion/extension
Foot	Ankle lateral Ankle medial	Metatarsal 1 Metatarsal 5	

JC: Joint centre; calc: Virtual markers calculated from the position of other markers

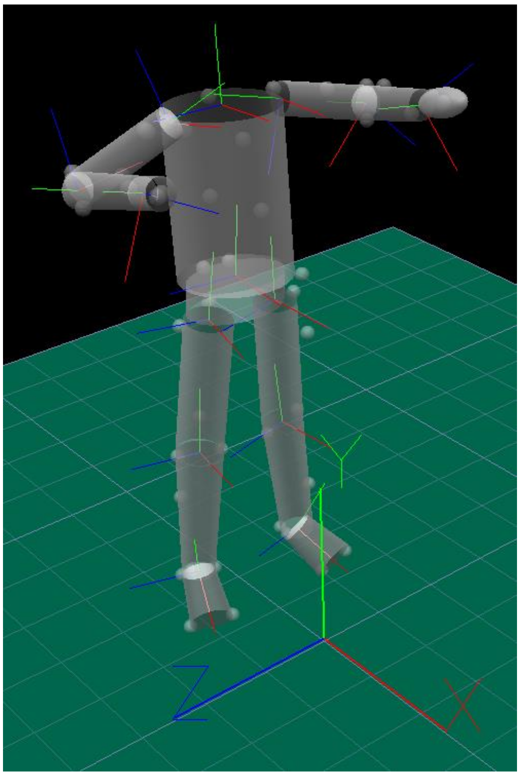

Figure 4-3: Illustration of Visual 3D model used for kinematic and kinetic analysis.

A limitation of the model used in this study is the simplification of the shoulder complex. Although the shoulder complex consists of the glenohumeral joint, the acromioclavicular joint, the sternoclavicular joint, and the scapulothoracic joint (Terry & Chopp, 2000), most studies analysing throwing motions model the shoulder as a single joint (Fleisig et al., 1995; Hirashima, Kudo, Watarai, et al., 2007; Hong et al., 2001; Hore et al., 2011; Roach et al., 2013). The simplification of the shoulder complex to the thoracohumeral joint is mainly caused by the difficulties to record scapula motions (Veeger et al., 2003). In the present study, the joint centre of the shoulder was calculated as the vertical projection from the marker placed on the acromion to the height of the marker placed on the lesser tuberosity of the humerus during a static trial with the arm fully adducted.

The lab coordinate system and the orientation of the local segment coordinate systems was as follows: +X/-X anterior/posterior, +Y/-Y superior/inferior, +Z/-Z medial/lateral (Figure 4-3). The joint rotation sequence used in this study was chosen to be the one recommended by ISB with the shoulder rotation sequence being Y-X-Y (Wu et al., 2005). This sequence has previously been used in studies analysing shoulder motion (Gasparutto et al., 2015; Oliver, Lohse, & Gascon, 2015; Saul et al., 2014). Even though some studies have used a different shoulder rotation sequence (Dillman et al., 1993; Roach et al., 2013), previous studies could not identify a single rotation sequence that would best describe the motion around all three axis (Phadke et al., 2011; Šenk & Chèze, 2006).

4.2.3.2. Data processing

In the present study, kinematic, kinetic, and temporal variables were analysed in order to test the hypotheses in relation to throwing performance and injury prevention. The data of the arm cocking phase and the arm acceleration phase were analysed in this study. The six phases of throwing are illustrated in Figure 4-4. The arm cocking phase starts with front foot contact and ends with maximum external shoulder rotation, and the arm acceleration phase starts with maximum external shoulder rotation and ends at ball release (Dillman et al., 1993; Werner et al., 1993). The only variable that was analysed outside of these phases was the maximum internal shoulder rotation velocity, which occurs after the ball is released. In order to compare the variables between the throws, all trials were time-normalised with the instant of front foot contact occurring at 0% and the instant of ball release at 100%. A similar approach has been used in several previous studies of throwing (Barrentine et al., 1998; Fleisig et al., 1996; Matsuo et al., 2001; Roach & Lieberman, 2014).

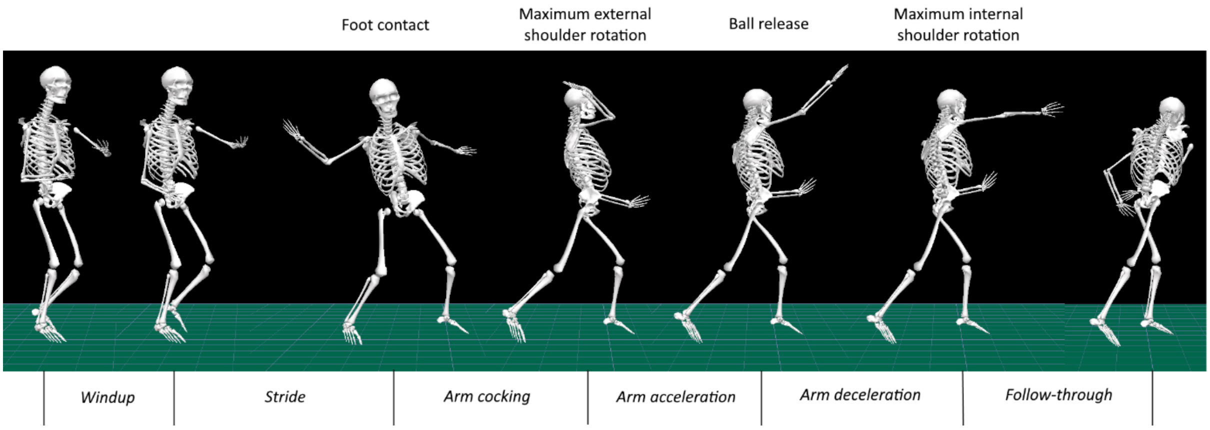

Figure 4-4: The six phases of throwing as described by previous research (Dillman et al., 1993; Werner et al., 1993).

Rotation around 10 degrees of freedom were calculated: three degrees of freedom at the trunk (tilt forward, tilt sideways, axial rotation); three degrees of freedom at the shoulder joint (horizontal adduction/abduction, shoulder adduction/abduction, internal/external rotation); one degree of freedom at the elbow (flexion/extension); one degree of freedom at the forearm (pronation/supination); one degree of freedom at the wrist joint (flexion/extension); and one degree of freedom at the knee of the lead knee (flexion/extension) (Figure 4-5 and Table 4-3). Before calculating the joint rotations, the position data of the markers were filtered using a low-pass filter with a cut-off frequency of 20 Hz. The cut-off frequency was determined by performing a residual analysis on five trials (Winter, 2009), and was the same as used in a previous study using a similar setup (Buffi et al., 2015).

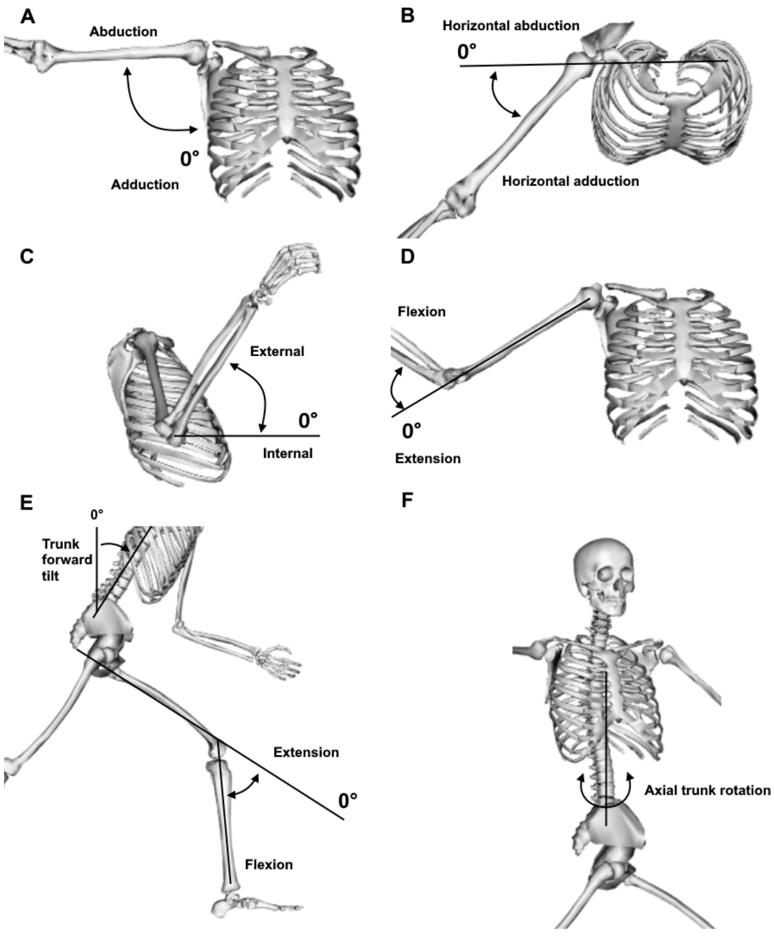

Figure 4-5: Definitions of kinematic variables: (A) shoulder adduction/abduction, (B) horizontal adduction/abduction, (C) shoulder internal/external rotation, (D) elbow flexion/extension, (E) lead knee flexion/extension and trunk forward tilt, (F) axial trunk rotation.

Joint torques were calculated for all three rotations of the shoulder joint, elbow flexion/extension torque, and elbow varus/valgus torque (Figure 4-6). Additionally, shoulder distraction/compression force at the shoulder was calculated (Figure 4-6). Joint torques were normalised by dividing the values by the participant's body height and body mass and multiplying by the average body height and body mass of all the participants, whereas the joint forces were normalised by dividing the values by the participant's body mass and multiplying by the average body mass (Fleisig et al., 1996).

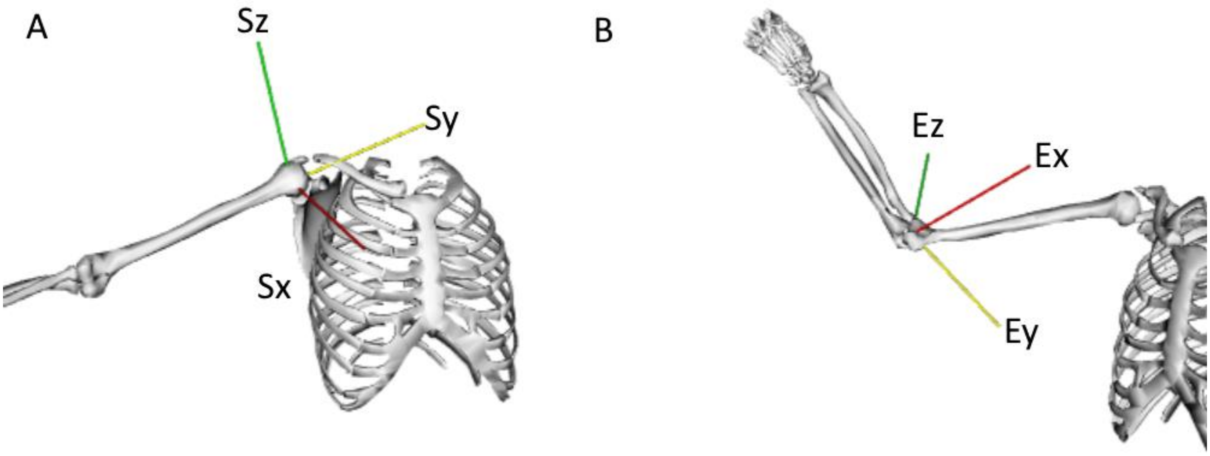

Figure 4-6: Anatomical reference frames of the shoulder (A) and elbow joints (B). Sy: Shoulder compression force (+), shoulder distraction force (-); Ex: axis of valgus (+)/ varus (-) torque.

Values at the instant of front foot contact, at the instant of ball release, and the maximum values of these variables were analysed as these have previously been identified as relating to either throwing performance or risk of injuries (Fleisig et al., 1996, 1995, 1999; Matsuo et al., 2001; Stodden et al., 2005; Werner et al., 2001, 2002). In addition to kinematic and kinetic variables, the ball release speed was calculated as the velocity of a virtual marker created at the midpoint between the two reflective markers attached to the ball. The instant of ball release was visually determined for each individual throw to be when the distance between the hand marker and the ball markers started to increase. The stride length was defined as the distance between the two ankle joint centres at the instant of front foot contact, and was reported as a percentage of total body height (Fleisig et al., 1996). The three fastest throws for each upper arm mass condition by each participant were chosen for the analysis in order to account for the variability of ball release speed and throwing technique within the throws performed by a participant (Bartlett, Wheat, & Robins, 2007; Fleisig, Chu, Weber, & Andrews, 2009). The average value across the three throws for each variable was used for each participant.

4.2.3.3. Statistical analysis

The statistical analysis was divided into two parts. First, a group analysis of the ball release speed, kinematic variables, kinetic variables, and temporal variables was performed. Additionally, the ball release speed was analysed for each participant individually in order to determine if all participants benefited from the additional upper arm mass.

Differences in ball release speed and throwing technique for all participants with additional upper arm mass were analysed using a repeated measures ANOVA test. If the main effect for upper arm mass was significant, follow-up t-tests (Bonferroni) were performed for each upper arm mass condition. Statistical significance was accepted at $p<0.05$. For data that were not normally distributed, the non-parametric Friedman’s ANOVA was used to analyse the data.

Due to the considerable inter-individual differences that might occur in ball release speed with additional upper arm mass, the ball release speed of each participant was analysed individually (Bates, James, & Dufek, 2004). In order to determine each participant's optimal upper arm mass, a straight line ($y = ax + b$) and a u-shape curve ($y = Y_M + c(x - X_M)^2$) were fitted to the ball release speed with changes in upper arm mass for each individual participant (Linthorne & Stokes, 2014). Akaike's Information Criterion (AIC) was calculated using GraphPad Prism version 7.00 (GraphPad Software, La Jolla, California, USA) in order to determine which of the two models better fits the data (Motulsky & Christopoulos, 2003). Details about how to calculate the AIC are provided in Appendix 1. The variables of the u-shape provide information about the maximum ball release speed achieved (Y_M) and the optimal upper arm mass (X_M). In case of a straight line being the best-fit model to the ball release speed with additional upper arm mass, the 95% confidence interval of the gradient (a) was analysed in order to determine the effect. If the 95% confidence interval of the gradient included zero, it was concluded that the additional upper arm mass did not affect the participant's ball release speed (Motulsky, 2013).

4.3. Results

4.3.1. Group analysis

Additional upper arm mass did not significantly affect ball release speed. Maximum external shoulder rotation decreased by about 5° for throws performed with 10% and 20% increase in upper arm mass. Throws executed with an additional 10% of mass attached to the upper arm produced 68°/s less shoulder adduction angular velocity and 30% of additional upper arm mass caused an increase in shoulder compression force by 35 N. No significant main effect was observed for the remaining kinematic and kinetic variables.

4.3.1.1. Ball release speed

A repeated measures ANOVA revealed no significant difference in ball release speed with changes in upper arm mass, $F(5, 60)=2.33$, $p=0.054$, $\eta_p^2=0.16$ (Figure 4-7, Table 4-4).

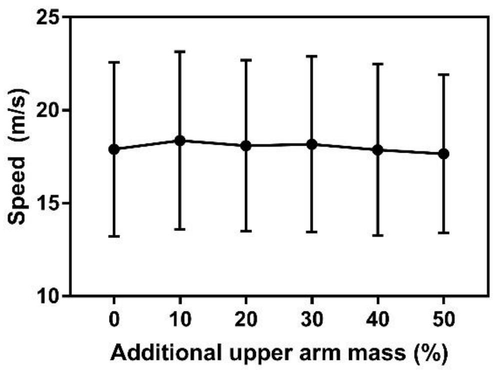

Figure 4-7: Ball release speed with various amounts of additional upper arm mass. No significant differences occurred with heavier upper arm masses.

4.3.1.2. Kinematic variables

Most of the angles at maximum value, at the instant of front foot contact, and at the instant of ball release did not significantly change with increased upper arm mass (Table 4-4). The only significant changes were for the maximum external shoulder rotation angle. Additional upper arm mass resulted in a significant main effect for maximum external shoulder rotation, $F(5, 60)=6.26$, $p<0.01$, $\eta_p^2=0.34$. Bonferroni post-hoc tests revealed that maximum external shoulder rotation significantly decreased with an additional 10% and 20% ($p<0.05$) of upper arm mass compared to the throws performed without additional upper arm mass. A decrease of about 5° was recorded.

A significant main effect for maximum shoulder adduction angular velocity was recorded with additional upper arm mass, $F(5, 60)=2.51$, $p<0.05$, $\eta_p^2=0.17$ (Table 4-5). A significant increase by 68°/s ($p<0.05$) in maximum shoulder adduction angular velocity was measured with an additional 10% of upper arm mass compared to the throws performed without additional upper arm mass. Repeated measures ANOVA for all remaining kinematic variables, including the timing of these variables, did not show any significant main effects between the different upper arm mass conditions.

4.3.1.3. Kinetic variables

Additional upper arm results in a significant difference in maximum shoulder compression force, $F(5, 60)=3.05$, $p<0.05$, $\eta_p^2=0.20$ (Table 4-5). Bonferroni post-hoc tests identified a significant increase by 35 N in maximum shoulder compression force ($p<0.05$) for the throws performed with an additional 30% of mass attached to the participants’ upper arm compared to the throws without additional upper arm mass. The remaining kinetic variables were not significantly affected by changes in the participants’ upper arm mass.

Table 4-4: Changes in ball release speed, stride length, and joint angles with additional upper arm mass (Mean, SD).Maximum external shoulder rotation significantly decreased with an additional upper arm mass of 10% and 20% compared to no additional upper arm mass.

	0%	10%	20%	30%	40%	50%	Significance
Ball release speed (m/s)	17.7 ± 5	18.1 ± 5	18.0 ± 4	18.0 ± 5	17.7 ± 5	17.5 ± 4	
Stride length (% BH)	40.4 ± 10	41.3 ± 10	42.5 ± 9	42.9 ± 9	43.1 ± 9	42.6 ± 8	
Maximum angles (°)							
Horizontal abduction	48.4 ± 14	47.6 ± 15	48.2 ± 15	47.9 ± 15	46.7 ± 16	45.8 ± 14	
Shoulder abduction	77.5 ± 15	78.1 ± 12	78.4 ± 11	77.3± 13	78.6 ± 11	79.9 ± 11	
External rotation**	**116 ± 15**[a,b]	**111 ± 15**[a]	**110 ± 12**[b]	112 ± 13	110 ± 13	110 ± 13	**a*; b***
Elbow flexion	137 ± 20	136 ± 19	136 ± 19	136 ± 18	136 ± 19	137 ± 19	
Angles at foot contact (°)							
Lead leg knee	29.4 ± 11	33.1 ± 12	32.7 ± 13	32.1 ± 13	33.1 ± 13	32.2 ± 12	
Horizontal abduction	-11.4 ± 24	-4.4 ± 26	-8.0 ± 23	-6.6 ± 25	-1.4 ± 27	-5.5 ± 23	
Shoulder abduction	55.4 ± 15	56.3 ± 17	55.2 ± 16	53.4 ± 16	55.9 ±16	58.2 ±16	
External rotation	43.4 ± 23	46.2 ± 26	39.6 ± 23	46.0 ± 24	48.7 ± 28	44.1 ± 27	
Elbow flexion	107 ± 23	105 ± 24	106 ± 22	107 ± 24	108 ± 23	109 ± 21	
Angles at ball release (°)							
Lead leg knee	33.0 ± 11	33.0 ± 11	35.1 ± 12	33.6 ± 13	34.2 ± 12	34.3 ± 13	
Trunk tilt forward	-1.8 ± 7	-0.5 ± 6	-1.1 ± 6	0.6 ± 7	-0.5 ± 6	-0.7 ± 6	
Trunk axial rotation	35.5 ± 11	38.6 ± 8	37.1 ± 9	38.4 ± 9	39.5 ± 12	38.6 ± 10	
Horizontal adduction	40.2 ± 15	39.1 ± 15	40.8 ± 17	40.2 ± 17	39.3 ± 17	39.3 ± 16	
Shoulder abduction	72.2 ± 16	70.5 ± 15	70.5 ± 15	70.6 ± 16	70.8 ± 15	70.7 ± 15	
External rotation	66.2 ± 17	65.6 ± 20	69.4 ± 17	66.1 ± 16	68.0 ± 17	70.1 ± 12	
Elbow flexion	54.1 ± 17	54.7 ± 20	56.0 ± 20	52.9 ± 20	52.3 ± 18	55.5 ± 17	

*p<0.05; **p<0.01; BH= body height;
a: significant difference between 0% and 10%; b: significant difference between 0% and 20%

Table 4-5: Changes in maximum joint angular velocities, maximum joint kinetics, and timing of kinematic variables with additional upper arm mass (Mean, SD). Maximum shoulder adduction angular velocity increased with an additional 10% and maximum shoulder compression force increased with an additional 30% of mass attached to upper arm.

	0%	10%	20%	30%	40%	50%	Significance
Maximum angular velocities (°/s)							
Shoulder adduction*	**329 ± 273[a]**	**397 ± 273[a]**	344 ± 293	348 ± 264	342 ± 259	322 ± 217	a*
Internal rotation	3160 ± 812	3160 ± 798	3060 ± 850	3010 ± 938	3040 ± 838	2980 ± 678	
Elbow extension	1810 ± 271	1880 ± 202	1810 ± 273	1810 ± 251	1820 ± 202	1760 ± 180	
Maximum joint kinetics							
Internal rotation torque (N·m)	51.6 ± 20	51.0 ± 16	54.4 ± 18	55.5 ± 18	55.8 ± 19	58.3 ± 20	
Elbow extension torque (N·m)	15.5 ± 5	16.2 ± 6	16.0 ± 5	17.4 ± 7	19.6 ± 8	16.7 ± 6	
Elbow valgus torque (N·m)	14.0 ± 5	13.7 ± 5	13.2 ± 5	13.6 ± 5	13.7 ± 5	13.4 ± 6	
Shoulder compression force (N)*	**258 ± 113[c]**	289± 127	273 ± 111	**291 ± 118[c]**	294 ± 114	294 ± 114	c*
Timing of kinematic variables (%)							
Max. ext. shoulder rotation	69.9 ± 145	72.5 ± 18	73.4 ± 14	72.7 ± 18	70.6 ± 22	70.9 ± 18	
Max. elbow flexion	69.4 ± 8	71.1 ± 11	70.8 ± 7	68.9 ± 10	67.6 ± 12	69.7 ± 10	
Max. horizontal abduction	89.4 ± 7	88.4 ± 9	90.0 ± 5	87.6 ± 5	87.1 ± 11	88.9 ± 6	
Max. shoulder abduction	68.2 ± 29	67.4 ± 32	67.4 ± 33	68.5 ± 32	68.1 ± 33	61.8 ± 35	
Max. int. shoulder velocity	105 ± 4	106 ± 5	105 ± 4	104 ± 4	105 ± 3	105 ± 3	
Max. elbow extension velocity	96.3 ± 3	97.9 ± 5	97.0 ± 3	96.4 ± 3	96.5 ± 2	96.9 ± 2	

*$p<0.05$;
a: significant difference between 0% and 10%; c: significant difference between 0% and 30%
Joint torques were normalised by body height and body mass.
Joint forces were normalised by body height.
Time is presented as percentage from foot contact (0%) to ball release (100%).

4.3.2. Individual analysis

Analysing the ball release speed with additional upper arm mass for each individual participant highlights that some participants benefited from increasing their upper arm mass (Figure 4-8 A). A u-shape was the best fit to the ball release speed for eight out of the thirteen participants (Table 4-6). The increase in ball release speed for these participants ranged between 0.04 m/s and 2.40 m/s. The optimal upper arm mass ranged between 7.3% and 34.6% of additional upper arm mass.

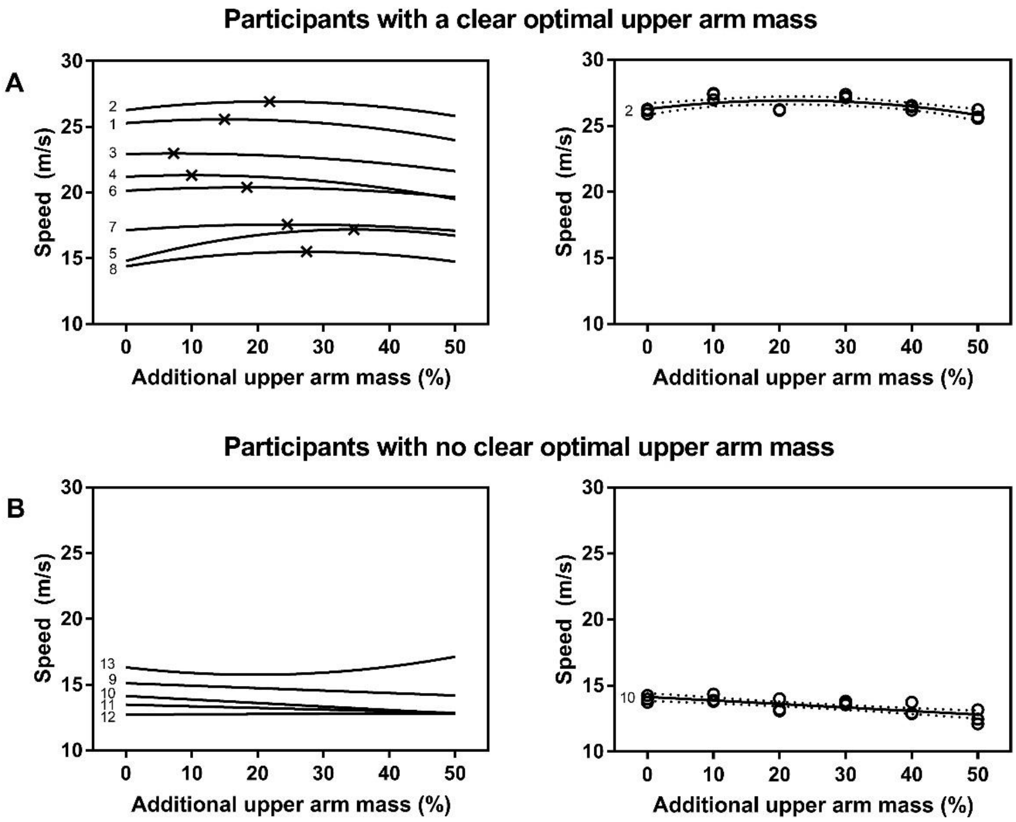

Figure 4-8: Ball release speed with additional upper arm mass for each individual participant. (A) The optimal upper arm mass (x) for 8 participants is higher than their actual upper arm mass. (B) 5 participants did not display an optimal upper arm mass within the range of masses tested. The ball release speed for each individual throw analysed for Participants 2 and 10 are presented including the best-fit curve with the 95% confidence interval (dashed lines).

A linear model was the best fit for four participants, with two showing no effect of additional upper arm mass and the other two showing a decrease in ball release speed as upper arm mass increased (Figure 4-8 B). One participant's ball release speed decreased with slight increases in upper arm mass, before increasing with heavier upper arm masses (Figure 4-8 B).

Table 4-6: Parameters of the linear models and u-shape models fitted to the ball release velocity for each participant. AICc was calculated to determine the probability of each model to better fit the data. The best-fit models are presented in bold.

Participant	**Linear Fit**			**U-shape**			
	Gradient ± 95% CI	**Yintercept**	**%***	**c**	**X_M ± 95% CI**	**Y_M**	**%***
1	-0.026 ± 0.017	25.7	12.6	**-0.0013**	**15.0**	**25.6**	**87.4**
2	-0.009 ± 0.018	26.7	7.4	**-0.0014**	**21.8**	**26.9**	**92.6**
3	-0.026 ± 0.011	23.2	25.3	**-0.0007**	**7.3**	**23.0**	**74.7**
4	-0.034 ± 0.016	21.6	18.6	**-0.0011**	**10.0**	**21.3**	**81.4**
5	0.039 ± 0.025	15.5	7.4	**-0.0020**	**34.6**	**17.2**	**92.6**
6	-0.010 ± 0.014	20.4	48.0	**-0.0007**	**18.4**	**20.4**	**52.0**
7	-0.001 ± 0.013	17.4	46.1	**-0.0007**	**24.5**	**17.6**	**53.9**
8	0.007 ± 0.022	14.9	24.7	**-0.0015**	**27.5**	**15.5**	**75.3**
9	**-0.019 ± 0.019**	**15.1**	**80.6**	0.0004	47.2	14.3	19.4
10	**-0.027 ± 0.012**	**14.2**	**66.6**	-0.0005	-1.6	14.0	33.4
11	**0.002 ± 0.017**	**12.7**	**76.4**	-0.0005	26.5	12.9	23.6
12	**-0.012 ± 0.010**	**13.5**	**64.3**	0.0004	39.6	13.0	35.7
13	0.016 ± 0.023	15.8	28.5	**0.0015**	**19.6**	**15.8**	**71.5**

X_M=Optimal upper arm mass; Y_M=Maximum ball release speed

*Probability of either the straight line or u-shape to best fit the data.

4.4. Discussion

The group analysis of the ball release speed with additional upper arm mass did not reveal a common optimal upper arm mass. None of the upper arm mass conditions resulted in a higher ball release speed. Furthermore, analysis of the throwing technique revealed differences in maximum external shoulder rotation for throws performed with an additional 10% and 20% of mass attached to the upper arm. Increasing the upper arm mass by 10% resulted in an increase in maximum shoulder adduction angular velocity, while an additional 30% of mass increased the shoulder compression force. None of the other kinematic, kinetic, or temporal variables changed between the upper arm mass conditions.

However, analysing the ball release speed of each individual participant revealed that the majority of the participants (8 out of 13) benefited from a heavier upper arm mass. The optimal upper arm mass varied between participants, which might be one of the reasons why no significant differences in ball release speed were observed between the mass conditions. Additionally, out of the eight participants that increased their ball release speed with a heavier upper arm mass, only two of them improved their ball release speed by more than a previous study in cricket bowling has identified to have an effect on the performance (Petersen, Wilson, & Hopkins, 2004). A participant's individual optimal upper arm mass, the small effect of additional upper arm mass on some participant's ball release speed, and the negative effect on the performance of some participants provided evidence that future studies should analyse each participant individually.

4.4.1. Throwing performance

Throwing a projectile is an important skill in some sports, where the goal is to throw the projectile as fast, as far, or as accurate as possible (eg. baseball, cricket, javelin throw, basketball). Apart from the release angle and the release height, the release velocity is the major contributor to the success in many of these sports (Linthorne, 2006). Thus, athletes and coaches try to maximise the release velocity in order to improve their performance. Previous research has focussed on various training programs in order to improve throwing performance (van den Tillaar, 2004), including training programs that involved throwing balls of various masses (Petersen et al., 2004; Wickington & Linthorne, 2017). However, only limited research has emphasised the idea of changing arm segment masses to maximise throwing performance.

4.4.1.1. Ball release speed

Throwing a projectile involves complex coordination between the body segments in order to reach a high velocity at the most distal segment of the kinetic chain (Putnam, 1993). As the kinetic chain relies on the conservation of angular momentum in order to increase the angular velocity, changes in segment mass and moment of inertia affect the outcome of the movement. Three previous studies have analysed the effect of arm segment mass on throwing performance, such as throwing as fast as possible (Southard, 1998), throwing as far as possible (Linthorne et al., n.d.), or horizontal arm swing velocity (Kim et al., 2008). All three studies and the two-dimensional simulation study performed in the previous chapter (Chapter 3) conclude that an athlete's throwing performance can be improved by increasing the upper arm mass. The findings of these studies would suggest that there is an optimal upper arm mass that results in the highest ball release speed, as has been observed in javelin throwing where the aim is to maximise the distance thrown (Linthorne et al., n.d.). However, no previous study has attempted to determine the optimal upper arm mass in a throw where the goal is to reach the highest ball release speed.

The present study did not identify an optimal upper arm mass that results in the maximum ball release speed across all participants (Figure 4-7 and Table 4-4). However, further analysis of the ball release speed for each individual participant highlighted that 8 out of 13 participants increased their performance with heavier upper arm masses (Figure 4-8 A and Table 4-6). Of the remaining five participants, two were not affected by additional upper arm mass (Figure 4-8 B). The ball release speed decreased as the upper arm mass increased for two participants, while one participant showed a negative effect with the lighter upper arm mass conditions, but benefited from the heavier upper arm masses. These differences between participants combined with the variability in optimal upper arm mass between participants suggest that there is not a common optimal upper arm mass that would benefit all athletes. Fitting a u-shape to the ball release speed of each participant revealed an optimal upper arm masses ranging from 7.3% to 34.6% of additional mass attached around the centre of mass of the upper arm. The highest increase observed in the present study was 2.4 m/s, but some of the participants only managed to slightly increase their ball release speed, with only participants increasing their ball release speed by more than 0.7 m/s, which makes a substantial difference in cricket bowling (Petersen et al., 2004)

The results of the present study show that optimising an athlete's upper arm mass could be beneficial in sports such as baseball where the aim is to maximise ball release speed. However, it has to be noted that not every athlete would benefit from a heavier upper arm mass. The findings of the present study extend our knowledge by highlighting that the optimal upper arm mass varies between participants, but athletes and coaches should be cautious when attempting to apply these findings by ensuring that the specific athlete benefits from a heavier upper arm mass and determining the athlete's optimal upper arm mass. Differences in the optimal upper arm mass between participants have previously been observed in javelin throwing (Linthorne et al., n.d.), and the present study confirms that this is also the case for throwing a baseball for maximum velocity.

The participants in the present study were not highly skilled throwers. It remains to be seen if highly skilled athletes are affected in the same way by additional upper arm mass. The ball release speeds achieved in the present study were comparable to those of youth baseball pitchers (Fleisig et al., 1999; Ishida, Murata, & Hirano, 2006; Sgroi et al., 2015; Wicke, Keeley, & Oliver, 2013), but lower than those of professional and college baseball pitchers (Fleisig et al., 2006, 1999; Whiteside, Martini, Zernicke, & Goulet, 2016). A previous study observed a positive relationship between the muscle volume of the upper arm of the throwing arm and the ball release speed in high-school baseball pitchers (Yamada, Yamashita, et al., 2013). Therefore, it might be that highly skilled throwers are already at their optimal upper arm mass through their sport-specific training. Further research involving highly skilled throwers is required in order to determine if their upper arm mass could be optimised.

The inclusion of female participants in the present study might have affected the outcome, as various studies have reported a "gender gap" in throwing performance (Ehl, Roberton, & Langendorfer, 2005; Lorson, Stodden, Langendorfer, & Goodway, 2013; Thomas, Alderson, Thomas, Campbell, & Elliott, 2010). The four participants that were not affected or negatively affected by additional upper arm mass were all female (Figure 4-8 B). Further research could provide an insight into how differences in body segment masses affect a female's ability to throw.

4.4.1.2. Throwing technique

Although previous studies have analysed the effect of additional upper arm mass on ball release speed, none of them have identified how changes in upper arm mass affect joint kinematics. In the present study, it was hypothesised that heavier upper arm masses would not affect joint kinematics. Retaining a similar throwing technique while improving performance might be an indication that optimising the upper arm mass improves the transfer of angular momentum between the heavy trunk segment and the much lighter upper arm.

In the present study, maximum external shoulder rotation decreased with an additional 10% or 20% of mass attached to the participant's upper arm (Table 4-4). Previous studies have identified that decreasing the maximum external shoulder rotation results in lower ball release speeds (Matsuo et al., 2001). However, as the ball release speed with additional upper arm mass in the present study did not change, the results suggest that the participants improved the transfer of momentum as they reached the same ball release speed while decreasing the range of motion about the longitudinal axis of the upper arm. The maximum external shoulder rotation values recorded in the present study are lower than the values reported for baseball pitchers (Dun et al., 2007; Escamilla et al., 2007), as the participants in the present study did not regularly engage in throwing-related sporting activities.

Optimising the upper arm mass did not affect any of the other angles of the shoulder or elbow. Shoulder abduction angles throughout the throws were less than the values reported in baseball pitching studies (Fleisig et al., 1996; Fortenbaugh & Fleisig, 2009). A previous study used three-dimensional simulations of baseball pitchers to determine that the optimal shoulder abduction angle to maximise hand velocity is about 90° (Matsuo et al., 2002). The differences in shoulder abduction angle between highly skilled throwers and the participants in this study are one of the reasons for the lower ball release speeds recorded in the present study. However, in the present study changing the participant's upper arm mass did not improve their shoulder abduction angle.

Attaching an additional 10% of mass to the participant's upper arm resulted in an increase in maximum shoulder adduction angular velocity (Table 4-5). Increasing the shoulder angular velocity has previously been identified as contributing to a higher ball release speed (Werner et al., 2008). Increasing the velocity of the shoulder joint could also assist elbow extension due to the interactions torques acting from the upper arm on the forearm (Hirashima, 2002). Additional upper arm mass did not affect the other angular velocities that were measured. Interestingly, even with a reduced external shoulder rotation the maximum internal shoulder rotation did not decrease. This suggests that the heavier upper arm mass enabled the participants to generate the same amount of internal shoulder rotation angular velocity even though they reduced the range of motion over which they accelerated their upper arm.

A study by Southard (1998) analysed the effect of additional masses attached to the arm segments on throwing. He found that heavier upper arm masses of around 1.4 kg resulted in improvements in the proximal-to-distal sequence in maximum linear segment velocities. Less skilled throwers were able to increase their ball release speed as the additional upper arm mass allowed them to benefit from a more advanced kinetic chain. In the present study, there were no changes in relative timing of key instances of the throwing motion with changes in upper arm mass.

Even though group analysis of the ball release speed did not identify a common optimal upper arm mass in overarm throwing, analysing the ball release speed of each participant individually showed that some athletes can benefit from additional upper arm mass (Figure 4-8). Eight of the thirteen participants in the present study increased their ball release speed with additional upper arm mass. However, the optimal upper arm mass varied between participants. These findings confirm those of previous studies and highlight the importance of determining each athlete's individual optimal upper arm mass (Linthorne et al., n.d.; Chapter 3).

4.4.2. Risk of injuries

The success of any intervention is determined by the effect it has on the risk of injuries as well as by the change in performance. Changes in throwing technique that result in higher stresses on the joints without increasing performance are pathomechanical changes (Fortenbaugh et al., 2009). The present study showed that additional upper arm mass improved throwing performance in some participants, but no study yet has analysed if additional upper arm mass increases the risk of injury.

In a simplistic application of Newton's second law of motion, an increase in mass must be accompanied by an increase in forces and torques if the acceleration is to remain constant. However, the kinetic chain in throwing is a complex sequence of actions so this simple argument might not hold (Fortenbaugh et al., 2009). A higher segment mass might not produce greater forces and torques as it might affect the mechanical efficiency of the throw (Fortenbaugh & Fleisig, 2009). Through proper technique, baseball pitchers have shown that they are able to reach higher ball release speeds while also reducing the stresses on their joints (Aguinaldo et al., 2007; Fortenbaugh & Fleisig, 2009).

Apart from higher ball release speeds, several kinetic variables have been identified as causing overuse injuries that arise from repeated stresses on athletes' shoulder and elbow joints. A major cause of shoulder injuries is a high compression force acting on the shoulder joint, which reaches more than 1000 N (Dillman et al., 1993; Werner et al., 2007). Ball velocity, maximum external shoulder rotation, elbow flexion, shoulder internal rotation torque, and shoulder abduction torque affect the magnitude of the shoulder compression force (Werner et al., 2001). The results of the present study show that increasing the upper arm mass by 30% causes an increase in shoulder compression force, thus increasing the load on the shoulder complex and increasing the risk of injury.

High elbow valgus torques are another common cause of overuse injuries in throwing sports (Fleisig et al., 1995; Werner et al., 2002). Maximal external shoulder rotation, elbow flexion angle, and shoulder abduction angles have been identified as affecting the generation of elbow valgus torque (Aguinaldo & Chambers, 2009; Matsuo et al., 2002; Werner et al., 2002). In the present study, changes in upper arm mass did not affect maximum elbow valgus torque, and so is not likely to increase the risk of injury. Furthermore, the reduction in maximum external shoulder rotation with 10% or 20% of additional upper arm mass by the participants in the present study might suggest a lower risk of injury. An increase in maximum external shoulder rotation has been identified to increase the risk of injuries (Werner et al., 2001).

The only difference in kinetic variables was observed with an additional 30% of mass attached to the participant's upper arm, which resulted in an increase in shoulder compression force. As additional upper arm mass had only limited effect on ball release speed, further research is required in order to confirm if optimising an athlete's upper arm mass increases the loads on the joints.

4.4.3. Limitations

Even though the present study showed that optimal upper arm mass can potentially help athletes improve their throwing performance, several limitations might restrict these findings from being applied to athletes. Firstly, the participants in the present study were not highly skilled throwers and were not regularly engaged in throwing sports. Therefore, it remains to be seen if the same outcome applies to highly skilled athletes or if their upper arm mass is already optimised through their training (Yamada, Yamashita, et al., 2013).

Furthermore, the simplification of the shoulder model used in the present study might have affected both kinematic and kinetic variables of the shoulder movement. However, the shoulder model used in the present study is similar to those used by most studies analysing overhead throwing. Incorporating the motions of the various joints of the shoulder complex into the model could improve our understanding, especially regarding the risk of injuries (Gasparutto et al., 2015). As the shoulder model used in the present study reported the movement at the shoulder joint as a single glenohumeral joint, the effect that additional upper arm mass has on the movement of the scapula and the clavicle are not known.

Additionally, the participant’s segmental inertial parameters were determined as a percentage of the total body mass (de Leva, 1996), which was used to calculate the additional mass that was attached to participant’s upper arm. Employing a more accurate method to determine subject-specific segmental inertial parameters could increase the accuracy of the masses attached to the participant’s upper arm. The method used in the present study might have affected the participant’s optimal upper arm mass.

4.4.4. Applications

The results of the present study confirm that athletes can improve their ball release speed by optimising their upper arm mass. However, as the optimal upper arm mass varies between participants, determining an athlete’s optimal upper arm mass is important in order to maximise their performance. Furthermore, kinematic and kinetic analysis of the throws performed with additional upper arm mass revealed that small increases in upper arm mass do not increase the joint forces and joint torques acting on the throwing arm, thus not increasing the risk of injuries. However, the increase in shoulder compression force with an additional 30% of mass attached to the upper arm might suggest that an upper arm mass heavier than the optimal mass could negatively affect the risk or injury. Therefore, athletes and coaches should determine an athlete’s optimal upper arm mass in order to maximise the outcome.

4.4.5. Further Work

As the optimal upper arm mass varies between participants, further research is needed in order to determine if an athlete’s optimal upper arm mass is affected by the throwing technique employed by each individual athlete. As not every participant in the present study benefited from a heavier upper arm mass to increase their ball release speed, it is unknown what causes the different outcomes with additional upper arm mass. Analysis of kinematic and kinetic variables for each participant individually could provide further insight into how to determine an athlete’s optimal upper arm mass.

As the throws performed in this study were neither sport-specific nor performed by high skilled athletes, further research needs to be done in order to determine the optimal upper arm mass for professional athletes of various sports. Due to the differences in throwing technique used in different sports (eg. baseball, cricket, javelin throw) the optimal upper arm mass might vary between sports or might not be applicable to every throwing technique. In javelin throwing, athletes can improve both their distance thrown and release velocity by optimising their upper arm mass (Linthorne et al., n.d.), but it is unknown if baseball pitchers or cricket bowlers could benefit from optimising their upper arm mass. Additionally, the differences in the mass of the object thrown in the different sports might affect an athlete's optimal upper arm mass.

4.5. Conclusions

In sports such as baseball, cricket, or javelin throw, athletes aim to maximise their release velocity in order to improve their performance. The results of the present study suggest that some athletes would benefit from a heavier upper arm mass in order to increase their ball release speed. Furthermore, in the present study there were no clear indications that a heavier upper arm mass would negatively affect an athlete’s risk of injury. However, as not every athlete benefits from a heavier upper arm mass and because the optimal upper arm mass varies between each individual athlete, coaches should be advised to determine an athlete’s optimal upper arm mass first before attempting to increase the upper arm mass through hypertrophy exercises.

Chapter 5: Additional upper arm mass does not have the same effect on each athlete's throwing mechanics.

5.1. Introduction

In many throwing sports, the athlete's goal is to throw a projectile as fast or as far as possible. Thus, in order to be successful, athletes attempt to maximise their release velocity (Bartlett, 2000). Professional baseball pitchers are able to reach ball release speeds of around 50 m/s through sequential proximal-to-distal movement of their body segments (Putnam, 1993). Several studies suggest that athletes can improve their ball release speed by increasing their upper arm mass (Kim et al., 2008; Southard, 1998). Furthermore, in my previous studies (Chapters 3 & 4) and in the study by Linthorne et al. (n.d.) there was an optimal upper arm mass that resulted in the highest ball release speed or the furthest distance thrown. However, in these studies the magnitude of the optimal upper arm mass varied between the participants.

5.1.1. Inertial parameters in throwing

Previous studies have shown that changes in the mass of the upper arm of the throwing arm affect the ball release speed. Southard (1998) found an increase of around 6.4% in ball release speed for the less skilled throwers when attaching around 1.4 kg of additional mass to the participant's upper arm. The increase in ball release speed was caused by an improved use of the kinetic chain, as the less skilled participant's upper arm movement lagged behind the trunk movement with additional upper arm mass. The study by Kim et al. (2008) measured a slight increase in horizontal arm swing velocity with 25% and 50% increase in upper arm mass. Linthorne et al. (n.d.) focussed on javelin throwers and observed that the optimal upper arm mass to achieve maximum release velocity and distance thrown is greater than the athletes' actual upper arm mass. The optimal upper arm mass in this study depended on the participant and resulted in an average increase in throw distance of 5.4%. These findings are similar to those obtained from the two-dimensional throw simulations in Chapter 3, where an optimal upper arm mass resulted in the highest ball release speed. The optimal upper arm mass in this study was more than double the upper arm mass of an average adult male. Also, the optimal upper arm mass was greater for throw simulations with a heavier forearm mass, and slightly lower for throw simulations with a greater shoulder torque.

Furthermore, kinematic and kinetic analysis of throws performed with additional upper arm mass revealed that a heavier upper arm mass has only limited effect on the athlete's throwing mechanics (Chapter 4). In my previous study, maximum joint angles, joint angles at the instant of ball release, maximum joint angular velocities, and maximum joint kinetics did not significantly change with additional upper arm mass, except for the maximum external shoulder rotation, maximum shoulder adduction angular velocity, and shoulder compression force. Increasing the participant's upper arm mass by 10% or 20% resulted in a decrease in maximum external shoulder rotation and an increase in maximum shoulder adduction angular velocity. An additional 30% of mass attached to the participant's upper arm caused a significant increase in shoulder compression force. However, group analysis in Chapter 4 did not result in a significant increase in ball release speed with additional upper arm mass. Nevertheless, the results of the Chapter 4 study suggest that the optimal upper arm mass varies between athletes, indicating that each athlete should be analysed individually in order to maximise performance without increasing the risk of injury.

Previous studies suggest that the optimal upper arm mass in overarm throwing depends on the athlete's forearm mass (Linthorne et al., n.d.; Chapter 3) and their skill level (Southard, 1998). However, it is unclear if the effect of additional upper arm mass on ball release speed depends on the athlete's throwing motion. Therefore, identifying differences in joint kinematic and kinetic variables between athletes that benefit from additional upper arm mass and those whose ball release speed is not affected or decreases with additional upper arm mass could provide insight into which athletes can benefit from a heavier upper arm mass. This information could help to determine the mechanisms that enable athletes to increase their ball release speed with additional upper arm mass.

5.1.2. Kinematic and kinetic variables in throwing

In overhead throwing, several kinematic variables have previously been identified to determine the ball release speed. One of the major contributors to a high ball release speed is the internal/external shoulder rotation. A study comparing a high velocity to a low velocity group of professional baseball pitchers recorded a higher maximum external shoulder rotation angle for the high velocity group by 13° on average (Matsuo et al., 2001). Similar findings were obtained in a study using college baseball pitchers (Werner et al., 2008) and between the dominant and non-dominant arm in recreational baseball pitchers (Gray, Watts, Debicki, & Hore, 2006). The ability of skilled throwers to reach larger external shoulder rotation angles is related to their lower humeral torsion, which has an impact on throwing performance (Roach et al., 2012; Roach & Richmond, 2015b).

A larger external shoulder angle allows skilled throwers to store more elastic energy in the shoulder (Roach et al., 2013) and, as a result, increase their maximum internal shoulder angular velocity (Gray et al., 2006). Similar results were seen between baseball pitchers of different stages of development, where college pitchers (7430 °/s ± 1270) generated higher internal shoulder velocities compared to high school pitchers (6820 °/s ± 1380) (Fleisig et al., 1999). The same differences were also observed within youth baseball pitchers, where higher internal shoulder velocities resulted in higher ball release speeds (Chen, Liu, & Yang, 2016). Studies analysing the contributions of segment rotations towards ball release speed confirmed these findings. Several studies identified the internal shoulder rotation to contribute the most towards the ball release speed (Hirashima, Kudo, Watarai, et al., 2007; Hirashima & Ohtsuki, 2008; Roach & Lieberman, 2014).

Additionally, maximum elbow extension velocity has been recognised as a key variable in overhead throwing. Within college baseball pitchers, faster elbow extension velocities were measured for the throws performed with higher ball release speeds (Werner et al., 2008). Similar results were observed between pitchers throwing with their dominant and non-dominant arm, where they did not manage to reach the same elbow extension velocities with their non-dominant arm (Gray et al., 2006) and between baseball pitchers of different stages of development (Chen et al., 2016; Fleisig et al., 1999). The angular velocity of the elbow extension during the acceleration phase proved to be one of the main contributors to ball release speed (Hirashima et al., 2008). However, whereas the shoulder rotations are mainly produced by the muscles that surround the shoulder joint (Hirashima et al., 2008; Naito & Maruyama, 2008), the elbow extension is mainly created by interaction torques (Hirashima et al., 2008), which are used to increase the velocity of the thrown projectile (Gray et al., 2006; Hirashima, 2002; Hirashima et al., 2003).

5.1.3. Aims of the study

Previous studies have shown that adding mass to the upper arm can increase throwing velocity (Kim et al., 2008; Southard, 1998) and that athletes can optimise their upper arm mass to maximise their ball release speed or the distance thrown (Linthorne et al., n.d.; Chapter 3). However, as not every athlete benefits from additional mass attached to their upper arm (Southard, 1998, Chapter 4), it is unclear if there are characteristics of an athlete's throwing technique that determine whether additional upper arm mass will increase the athlete's throwing velocity. Therefore, the main aim of the present study was to determine if the effect of additional upper arm mass on ball release speed can be predicted by kinematic or kinetic variables of an athlete's throwing technique. In order to reach these aims, the present study was divided into two parts, using both an experimental and a simulation approach. This approach was selected in order to identify if an athlete's optimal upper arm mass could be determined using a simulation model and if a similar optimal upper arm mass could be confirmed by analysing experimentally collected data from athletes throwing a ball with additional mass attached to their upper arm..

5.1.4. Hypotheses

The hypotheses that were tested in the present study were:

- The optimal upper arm mass for a participant can be predicted by performing overarm throwing simulations using a three-dimensional upper-body model.

- The optimal upper arm mass for a participant determined from the simulations is similar to the optimal upper arm mass determined in a throwing experiment.
- The effect of additional upper arm mass on ball release speed is caused by differences between participants in maximum joint angles, joint angles at the instant of ball release, maximum joint angular velocities, and maximum joint torques.

5.2. Methods

In the present study, participants were asked to throw a baseball as fast as possible with a range of masses attached to their upper arm. Ethics approval was obtained from the College of Health and Life Sciences at Brunel University London. The study was divided into four parts in order to identify the kinematic, kinetic, and temporal variables that determine the effect of additional upper arm mass on throwing velocity:

- Three-dimensional throwing simulations with changes in upper arm mass.
- Analysis of experimental throws with changes in upper arm mass.
- Comparison of experimental throws to simulated throws.
- Identifying mechanisms that determine an athlete's optimal upper arm mass.

In the first part, throwing simulations with changes in upper arm mass were performed using a three-dimensional torque-driven upper-body model. The experimental data and the simulated data were analysed using an upper body model (Saul et al., 2014) in OpenSim 3.4 (Delp et al., 2007). In the second part, the throws performed with additional upper arm mass were analysed. The experimental throws were compared to the simulated throws in order to identify the mechanisms that cause changes in ball release speed with changes in upper arm mass. As the optimal upper arm mass varies between participants (Linthorne et al., n.d.; Chapters 3 & 4), a single-subject approach was used to determine how each participant's throwing motion is affected by a heavier upper arm mass (Bates et al., 2004).

5.2.1. Participants

Six healthy adults (4 male, 2 female) participated in the study (Table 5-1). At the start of the session, all participants signed an informed consent form. The participants were all physically active, but none regularly practiced a sport where throwing a projectile as fast as possible was required on a regular basis (eg. baseball, cricket, javelin throw). All participants were free of injuries and reported that they never had a shoulder injury requiring surgery.

Table 5-1: Characteristics of the participants (mean, SD). n=6

Participant	Gender	Height (cm)	Mass (kg)	Upper arm length (cm)	Calculated upper arm mass (kg)
1	Male	178	82	31	2.2
2	Male	172	76	31	2.2
3	Male	187	77	32	2.1
4	Male	177	65	30	1.8
5	Female	164	58	29	1.5
6	Female	168	65	27	1.7
Average		174 ± 8	71 ± 9	30 ± 2	1.9 ± 0.3

5.2.2. Data collection

Data collection was conducted in the Biomechanics Laboratory at Brunel University London. Before the start of the testing, the upper arm mass for each participant was calculated from their total body mass (Female: 2.55%; Male: 2.71%) (de Leva, 1996). The additional masses attached to the participant's upper arm during the testing procedure was 10%, 20%, 30%, 40% and 50% of the participant's upper arm mass (Table 5-2). The additional masses ranged from 0.15 kg to 1.12 kg.

The mass attached to the participant's upper arm consisted of lead shot and was fixed using a cohesive bandage (Vet-Wrap) that allowed the participant to throw without restricting their movement.

Table 5-2: Mean upper arm mass attached to the participant's upper arm for each condition.

Mass condition	Average (kg)	Range (kg)	
10%	0.19	0.14	0.22
20%	0.38	0.28	0.44
30%	0.56	0.42	0.66
40%	0.75	0.56	0.88
50%	0.93	0.70	1.10

At the beginning of the session, the participant performed a self-selected set of warm-up and stretching exercises (Oliver et al., 2011). The participant performed a set of throws to become familiar with the new task and avoid learning effects during the test (Hopkins, 2000). In the test, the participant was asked to throw a baseball (148 g) as fast as possible towards a target placed 3 m in front of them at the height of their shoulder (Figure 5-1). The target consisted of a cross (30 cm x 30 cm) marked on a curtain, but the accuracy of the throws was not recorded. While throwing the ball, the participant was sitting on a chair. This position was designed to restrict movement of the trunk. This restricted throwing motion was chosen to enable comparison between the simulated throws and experimental throws. The participant was not given feedback about their throwing performance (Štirn et al., 2017).

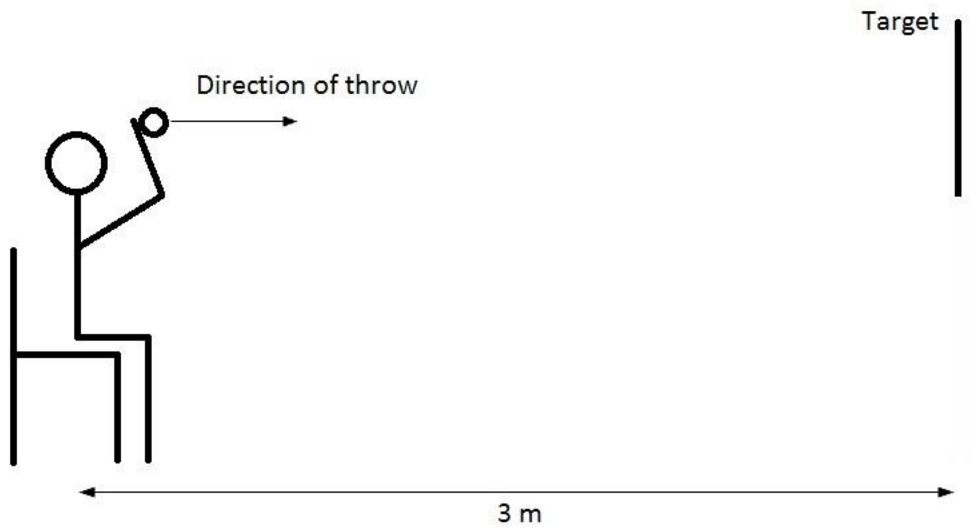

Figure 5-1: Illustration of the experimental setup with the participant sitting on a chair while throwing a baseball as fast as possible at a target.

During the testing session, the participant threw the baseball five times for each upper arm mass condition. The order of the upper arm mass conditions was randomised to avoid that the order affects the outcome of the study. In between each upper arm mass condition, the participant rested for about two to three minutes, before continuing with the next upper arm mass condition.

Eleven reflective markers were positioned on the participant's trunk and throwing arm (Figure 5-2). Two markers were placed on the baseball, exactly opposite to each other. These markers were used to calculate the position of the centre of mass of the ball and, through differentiation, the ball release speed. Motion analysis data of the throws were recorded at 150 Hz using 10 infrared LED cameras (Motion Analysis, Santa Rosa, USA). The motion analysis data were analysed using OpenSim 3.4 (Delp et al., 2007).

Figure 5-2: Marker set used for data collection, anterior view (left) and posterior view (right)

5.2.3. Model description

5.2.3.1. Hardware

The experimental data and simulations of this study were processed using OpenSim version 3.4 on a laptop with Microsoft Windows 10 (Microsoft, Redmond, WA, USA), with an Intel® Core™ i7-4500U 1.8 GHz and 8GB of memory.

5.2.3.2. Challenges faced while simulating overhead throws

The original idea of the present study was to simulate an overhead throwing motion with changes in upper arm mass using a full-body model. However, due to computational limitations in both hardware and software, the motion analysed in the present study was restricted to a three-dimensional movement of the arm segments. The first attempts to process, analyse, and simulate data of an overhead throw were performed using a comprehensive full-body model combining several models that had previously been created to analyse movements such as walking, running, jumping, or reaching (Anderson & Pandy, 1999, 2001, Delp et al., 1990, 2007; Holzbaur, Murray, & Delp, 2005; Yamaguchi & Zajac, 1989). However, due to the constraints on the movement of the upper body, the Inverse Kinematics tool in OpenSim 3.4 was not able to come to a solution. Removing the constraints of the upper body and increasing the range of motion at the shoulder joint allowed the software to find a solution for the Inverse Kinematics tool. However, due to the time required to compute joint angles (3 to 4 hours per throw) and the inability to generate joint torques for this model, a simpler model had to be employed.

Unfortunately, similar challenges were encountered when using a full-body model with a simplified shoulder joint (Hamner, Seth, & Delp, 2010). This model was initially developed to analyse running and so the shoulder movement was restricted to the glenohumeral joint, which is a common simplification in a three-dimensional analysis of throwing (Buffi et al., 2015; Fleisig et al., 1996; Roach et al., 2013). However, due to the complexity of the model, Inverse Kinematics and simulations in OpenSim 3.4 were not always able to come to a solution, or the movement diverged from the original movement.

As all attempts to use a full-body model to simulate overhead throwing failed, the analysis was reduced to the upper body only. An upper body model consisting of the trunk and the right arm was used in the present study (Saul et al., 2014). The model used was developed to simulate reaching movements and was later modified in order to be compatible with OpenSim 3.4. The trunk movement in the reaching simulations performed in the study by Saul et al. (2014) was restricted and attempts to include trunk movement into the throwing simulations were unsuccessful. Therefore, the throws analysed in the present study were restricted to the movement of the arm segments.

5.2.3.3. Three-dimensional model

The upper body model used in the present study (Saul et al., 2014) is based on a previously developed model (Holzbaur et al., 2005) and adapted to be compatible with OpenSim versions 3.2 and later. The model described by Saul et al. (2014) has seven degrees of freedom: shoulder horizontal adduction/abduction, shoulder adduction/abduction, shoulder internal/external rotation, elbow flexion/extension, pronation/supination, wrist flexion/extension, and wrist deviation. The order of joint rotations used in the upper body model are those recommended by the International Society of Biomechanics (Wu et al., 2005).

The inertial parameters for the humerus, radius, ulna, and hand segments of the model are based on previous research (Blana, Hincapie, Chadwick, & Kirsch, 2008; Clauser, McConville, & Young, 1969; McConville, Churchill, Kaleps, Clauser, & Cuzzi, 1980; Reich & Daunicht, 2000). Furthermore, the upper body model includes fifty musculotendon actuators.

5.2.3.4. Modifications to the upper body model

To enable the upper body model to be used to analyse and simulate overhead throwing, several parameters in the original model had to be modified. The mass of the hand segment was increased to be equal to the mass of the hand and ball. To increase computation efficiency and prevent the simulations from diverging, the degrees of freedom were reduced by fixing pronation/supination, wrist flexion/extension, and wrist deviation. As a result, the model used in the present study had only four degrees of freedom (Figure 5-3). Previous studies have identified that neither wrist movement nor forearm pronation/supination have a substantial impact on ball release speed (Hirashima, Kudo, Watarai, et al., 2007; Hirashima et al., 2003), and so omitting movement of these joint rotations from the analysis was not expected to affect the outcome of the study.

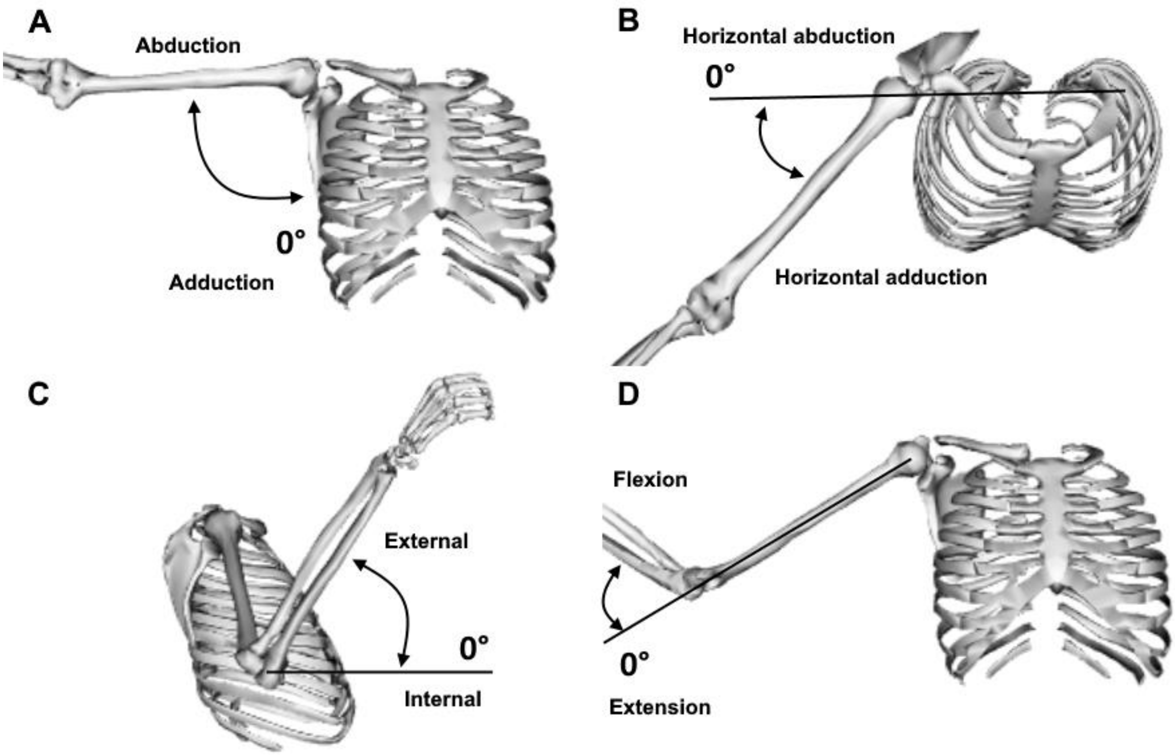

Figure 5-3: Definitions of joint rotations: A shoulder adduction/abduction, B horizontal shoulder adduction/abduction, C internal/external shoulder rotation, D elbow flexion/extension.

Additionally, the range of motion of several joint rotations had to be increased because some of the maximum joint angles reached by the participants exceeded the initial limits of the upper body model (Saul et al., 2014). The joint rotation ranges of motion for the original upper body model and the modified model used in the present study are presented in Table 5-3. Furthermore, the muscle actuators in the upper body model were replaced by torque actuators. Six different models were created with changes in upper arm mass and moment of inertia. The upper arm mass and the moment of inertia around all three axis were increased by 10%, 20%, 30%, 40%, and 50% from the values of the original upper body model.

Table 5-3: Modifications to the joint ranges of motion in the upper body model of Saul et al. (2014).

	Saul et al. (2014)		Modified model	
	Upper limit	Lower limit	Upper limit	Lower limit
Horizontal adduction/abduction (°)	100	-60	130	-90
Shoulder adduction/abduction (°)	150	30	180	0
Internal/external rotation (°)	-10	-60	20	-90
Elbow flexion/extension (°)	85	14	130	0

5.2.4. Data processing

5.2.4.1. Experimental throws

In OpenSim 3.4, the model was scaled to fit the dimensions of each participant. Virtual markers were placed on the OpenSim model in the same locations as those placed on the participant during data collection. The Scale tool in OpenSim was used to scale the segment dimensions of the model to the dimensions of the participant by matching the distances between the virtual markers and the markers placed on the participant. The scaled model for each participant was within the accuracy recommended by the guidelines from the software developers (Hicks, Uchida, Seth, Rajagopal, & Delp, 2015). The maximum marker error was less than 2 cm and the root mean square error was less than 1 cm.

Joint angles were computed using the Inverse Kinematics tool in OpenSim 3.4. The scaled model and experimental marker trajectories were used to generate the joint angles that best reproduced the throwing motion. The recommended guidelines for the accuracy of the Inverse Kinematics tool were followed for every processed throwing motion (Hicks et al., 2015); maximum marker error was less than 4 cm and root mean square error less than 2 cm. For all further analysis, the joint angles were low-pass filtered with a cut-off frequency of 20 Hz. The cut-off frequency was determined using residual analysis (Winter, 2009) and was the same as previously used in a baseball pitching study (Buffi et al., 2015). The residual analysis was performed on five randomly selected trials and five randomly selected markers for each trial.

The Inverse Dynamics tool and Analyze tool in OpenSim 3.4 were used to obtain joint torques, joint velocities, joint accelerations, and segment velocities. The Inverse Dynamics tool calculates the joint torques that cause the movement previously computed by the Inverse Kinematics tool. The Inverse Dynamics tool solves the equations of motion taking into account the properties of the model used and the motion analysed. In this study, the data were analysed from the instant of maximum horizontal shoulder abduction angle to the instant of ball release (which was taken as the instant of maximum hand velocity). For each participant, the three fastest throws for each upper arm mass condition were chosen for further analysis.

5.2.4.2. Simulated throws

The joint torques for the three fastest throws without additional upper arm mass by the participant were used to drive the three-dimensional throw simulations. For each throw, six simulations were performed with 0%, 10%, 20%, 30%, 40% and 50% increase in upper arm mass, resulting in 108 simulated throws across all 6 participants (6 participants, 3 throws per participant, and 6 mass conditions). As in the experimental throws, the simulated throws started at the time of minimum horizontal adduction and ended with maximum horizontal hand velocity. Joint kinematics were generated in order to analyse the differences between the different upper arm mass conditions.

5.2.5. Data analysis

A single-subject analysis approach was used in the present study as previous studies indicated that the optimal upper arm mass might be unique to the participant (Linthorne et al., n.d.; Chapter 4).

5.2.5.1. Simulated throws

The simulated throws did not include a ball segment therefore the instant of maximum hand velocity was taken as the instant of ball release, and the maximum hand velocity was taken as the ball release speed. A similar approach was previously used in a study performing three-dimensional throwing simulations to determine the optimal shoulder abduction angle in overarm throwing (Matsuo et al., 2002). The ball release speed for each simulated throw was plotted against the additional upper arm mass. A straight line ($y = Gradient \cdot x + Yintercept$) was fitted to the data, where the gradient represented the effect of additional upper arm mass on ball release speed.

The kinematic and kinetic variables of the simulated throws were plotted against the rate of change in ball release speed (gradient) with increasing upper arm mass in order to determine which variables affect the outcome of the throw simulations. Analysing kinematic and kinetic variables in relation to the effect of additional upper arm mass on ball release speed was employed to determine why differences between the throws occurred. The changes in joint angular velocities between the throws simulated with an increase in upper arm mass by 50% and the throws performed without additional upper arm mass were analysed to identify how a heavier upper arm mass affected the joint angular velocities. Additionally, the maximum joint angles, maximum joint angular velocities, and maximum joint torques of the throws performed without additional upper arm mass were plotted against the rate of change in ball release speed with increasing upper arm mass in order to identify if differences in joint kinematics or joint kinetics determine the outcome of the simulations. The correlation coefficient (*r*) was calculated to determine the linear relation between the kinematic/kinetic variables and the rate of change in ball release speed. An *r* value of ± 0.7 is considered a very strong correlation, ± 0.5 a strong correlation, ± 0.3 a moderate correlation, and ± 0.1 a weak correlation (Cohen, 1988). As recommended by Batterham and Hopkins (2006), the 90% CI of the correlation coefficient was calculated using the Fisher z transformation using a spreadsheet provided by Hopkins (2007). Analysis of the simulated throws was performed using GraphPad Prism version 7.00 (GraphPad Software, La Jolla, California, USA).

5.2.5.2. Experimental throws

Ball release speed, kinematic variables, and kinetic variables were plotted against the additional upper arm mass that was attached to the participant's throwing arm. A straight line ($y = Gradient \cdot x + Yintercept$) and a u-shape ($y = Y_M + c(x - X_M)^2$) were fitted to all variables for the three throws performed by the participant in order to determine the effect of additional upper arm mass on the variable. Akaike's Information Criterion (AIC) was used to determine which of the two models was a better fit to the data (Motulsky & Christopoulos, 2003). The AIC values were calculated using GraphPad Prism version 7.00 (GraphPad Software, La Jolla, California, USA) and details on how the AIC is calculated are presented in Appendix 1. In the case that the straight line was the best fit to the data, the gradient represented the effect of additional upper arm mass and the 95% CI was used to determine if the analysed variable was affected by changes in upper arm mass (Motulsky, 2013). In the case that the inverted u-shape was the best fit to the variable analysed, X_M represented the participant's optimal upper arm mass and Y_M was the maximum ball release speed.

5.3. Results

5.3.1. Simulated throws

5.3.1.1. Ball release speed

The throw simulations showed differences in the strength of the effect of upper arm mass on ball release speed (Figure 5-4). A straight line was a good fit for all data, except for one set of throws by Participant 3. The characteristics of the straight lines fitted to the throws are presented in Table 5-4. Some throws showed a positive effect of upper arm mass on ball release speed, whereas other throws showed a negative effect.

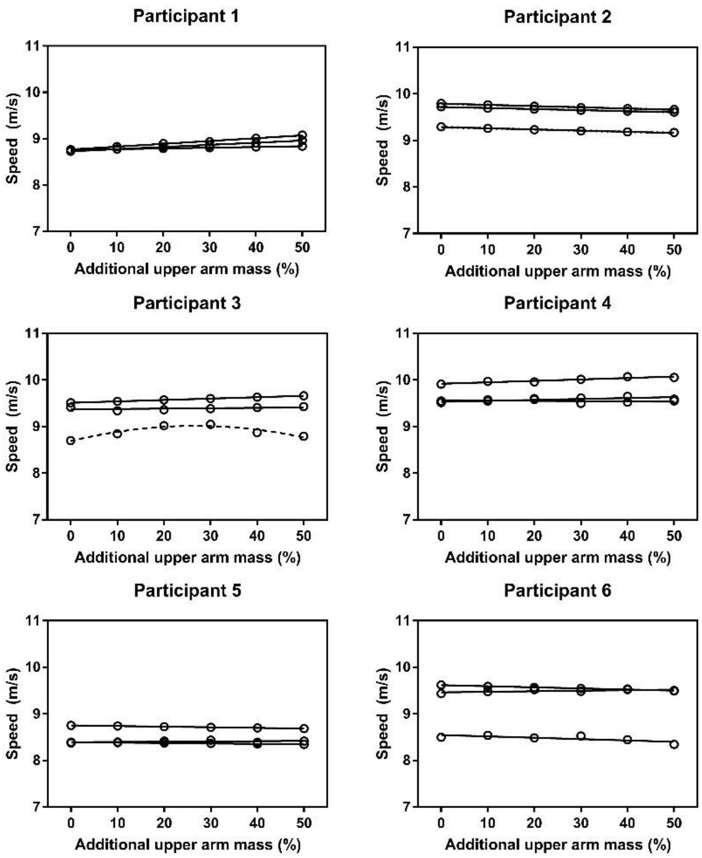

Figure 5-4: Changes in ball release speed with additional upper arm mass for the simulated throws. A linear model was the best fit for the majority of the sets of throws.

Table 5-4: Details about the straight lines fitted to the ball release speed for each set of simulated throws.

	Gradient (m/s per %)	Yintercept (m/s)
Participant 1	0.0061	8.8
	0.0046	8.7
	0.0016	8.8
Participant 2	-0.0023	9.7
	-0.0025	9.3
	-0.0026	9.8
Participant 3	0.0008	9.4
	0.0030	9.5
	———	——
Participant 4	-0.0007	9.6
	0.0020	9.5
	0.0031	9.9
Participant 5	0.0006	8.4
	-0.0009	8.4
	-0.0013	8.7
Participant 6	-0.0024	9.6
	0.0012	9.5
	-0.0029	8.5

Figure 5-5 shows that ball release speed was not related to the rate of change in ball release speed with increasing upper arm mass (Table 5-5).

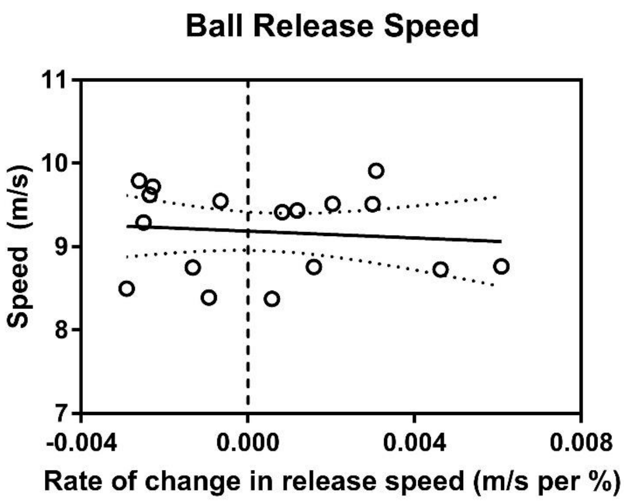

Figure 5-5: Ball release speed of the throws performed without additional upper arm mass in relation to the rate of change in ball release speed with increasing upper arm mass.

Table 5-5: Parameters of the correlation between kinematic and kinetic variables to the rate of change in ball release speed with increasing upper arm mass. A strong correlation between the rate of change in release velocity and the variable is indicated in bold.

	Gradient ± 95% CI	*r* ± 90% CI
Ball release speed (m/s per m/s per %)	-21 ± 105	-0.11 ± 0.41
Change in angular velocity (50%-0% condition)		
Horizontal shoulder adduction (°/s per m/s per %)	-786 ± 2370	-0.18 ± 0.40
Shoulder adduction (°/s per m/s per %)	-445 ± 863	-0.27 ± 0.39
Internal shoulder rotation (°/s per m/s per %)	**18000 ± 7800**	**0.78 ± 0.18**
Elbow extension (°/s per m/s per %)	**6770 ± 5390**	**0.57 ± 0.30**
Maximum joint angle		
Horizontal shoulder abduction (° per m/s per %)	**-1240 ± 910**	**-0.60 ± 0.28**
Shoulder abduction (° per m/s per %)	-535 ± 1890	-0.15 ± 0.41
External shoulder rotation (° per m/s per %)	-1280 ± 2700	-0.25 ± 0.39
Elbow flexion (° per m/s per %)	-1200 ± 2490	-0.26 ± 0.39
Maximum joint angular velocity		
Horizontal shoulder adduction (°/s per m/s per %)	-3300 ± 7910	-0.22 ± 0.40
Shoulder adduction (°/s per m/s per %)	12100 ± 14600	0.41 ± 0.35
Internal shoulder rotation (°/s per m/s per %)	-12000 ± 49800	-0.13 ± 0.41
Elbow extension (°/s per m/s per %)	-8070 ± 28500	-0.15 ± 0.41
Maximum joint torque		
Horizontal shoulder adduction (N·m per m/s per %)	5130 ± 23500	0.12 ± 0.41
Shoulder adduction (N·m per m/s per %)	18400 ± 15000	0.12 ± 0.41
Internal shoulder rotation (N·m per m/s per %)	-355 ± 3040	-0.06 ± 0.41
Elbow extension (N·m per m/s per %)	932 ± 1330	0.36 ± 0.37

r : correlation coefficient

5.3.1.2. Effect of additional upper arm mass on joint angular velocities

Attaching an additional 50% resulted in a decrease in internal shoulder rotation angular velocity for most sets of throws (Figure 5-6). The change in internal shoulder rotation angular velocity (very strong correlation) and elbow extension angular velocity (strong correlation) with additional upper arm mass was related to the rate of change in ball release speed (Table 5-5). The set of throws that were positively affected by additional upper arm mass showed a smaller reduction in internal shoulder rotation angular velocity, leading to an increase in elbow extension angular velocity.

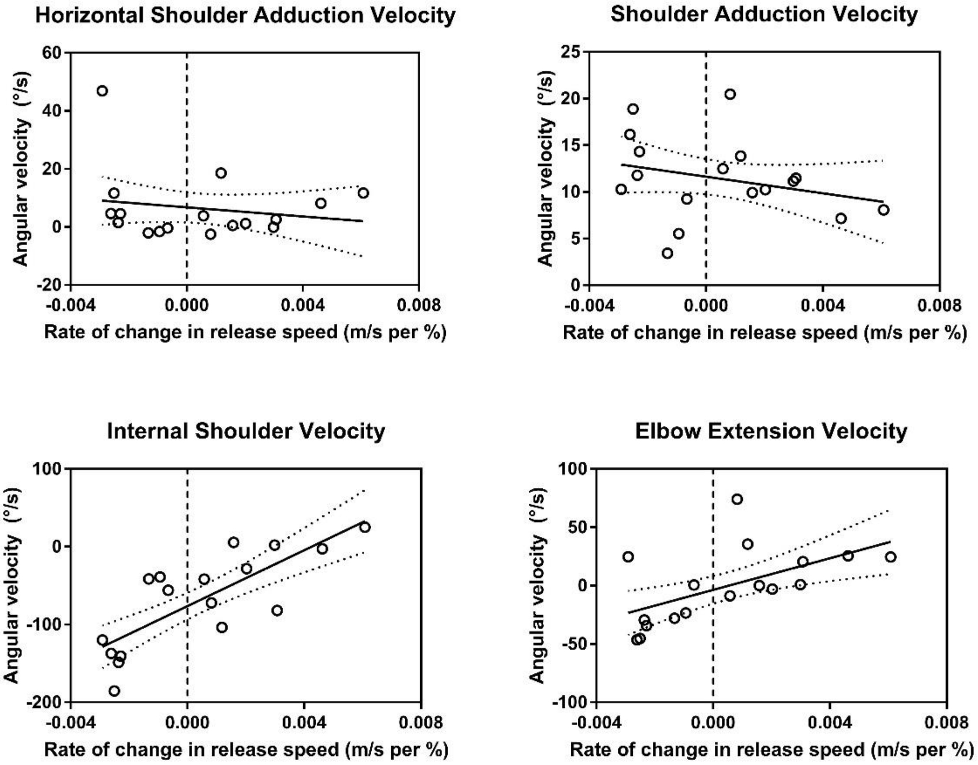

Figure 5-6: Changes in maximum joint angular velocities between the throws simulated without additional upper arm mass and the throws simulated with a 50% increase in upper arm mass. The internal shoulder rotation angular velocity and elbow extension angular velocity are strongly correlated to the rate of change in ball release speed with additional upper arm mass.

5.3.1.3. Maximum joint angles of throws without additional upper arm mass

There was a strong negative correlation between the maximum horizontal shoulder abduction angle and the rate of change in ball release speed (Figure 5-7). Throws that reached higher maximum horizontal shoulder abduction angles tended to produce a lower rate of increase in ball release speed with increasing upper arm mass (Table 5-5). No strong correlations for the other values were observed.

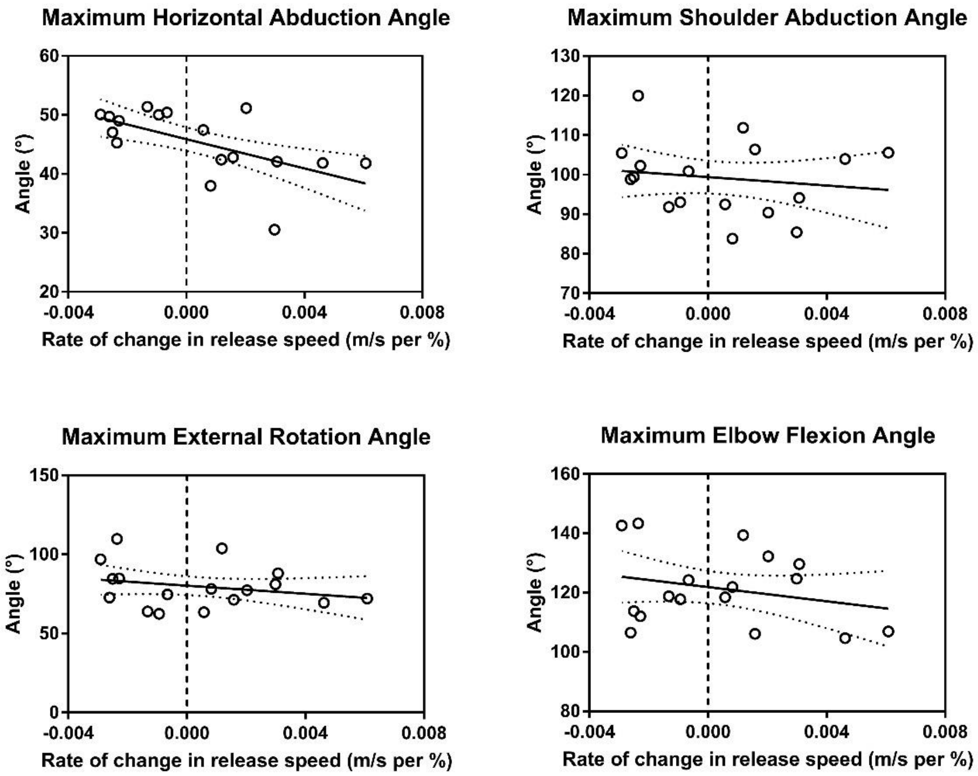

Figure 5-7: Maximum joint angles for throws performed without additional upper arm mass in relation to the rate of change in ball release speed with increasing upper arm mass. A strong negative correlation between the maximum horizontal shoulder abduction angle and the rate of change in release velocity was observed.

5.3.1.4. Maximum joint angular velocities of throws without additional upper arm mass

No strong positive or negative correlations were observed between the maximum joint angular velocities of the throws performed without additional upper arm mass and the rate of change in ball release speed with increasing upper arm mass (Figure 5-8 and Table 5-5).

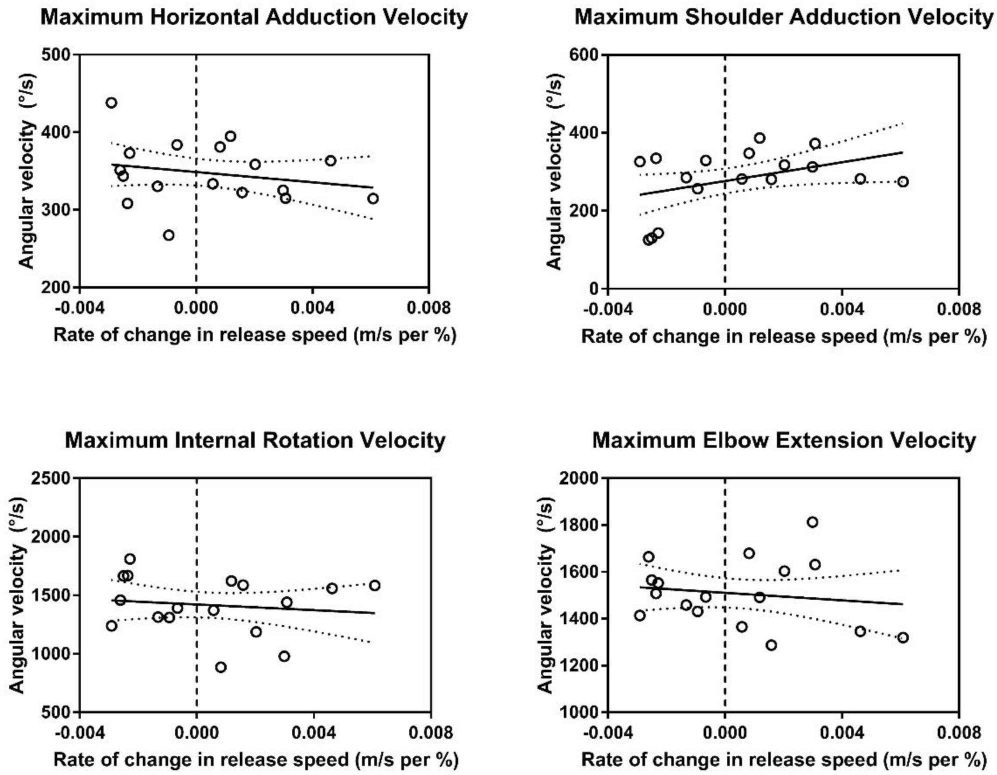

Figure 5-8: Maximum joint angular velocity for each throw performed without additional upper arm mass in relation to the rate of change in ball release speed with increasing upper arm mass. No strong correlations were observed.

5.3.1.5. Maximum joint torques of throws without additional upper arm mass

No strong correlations were observed between the maximum joint torques used to drive the throw simulations and the rate of change in ball release speed with increasing upper arm mass (Figure 5-9 and Table 5-5).

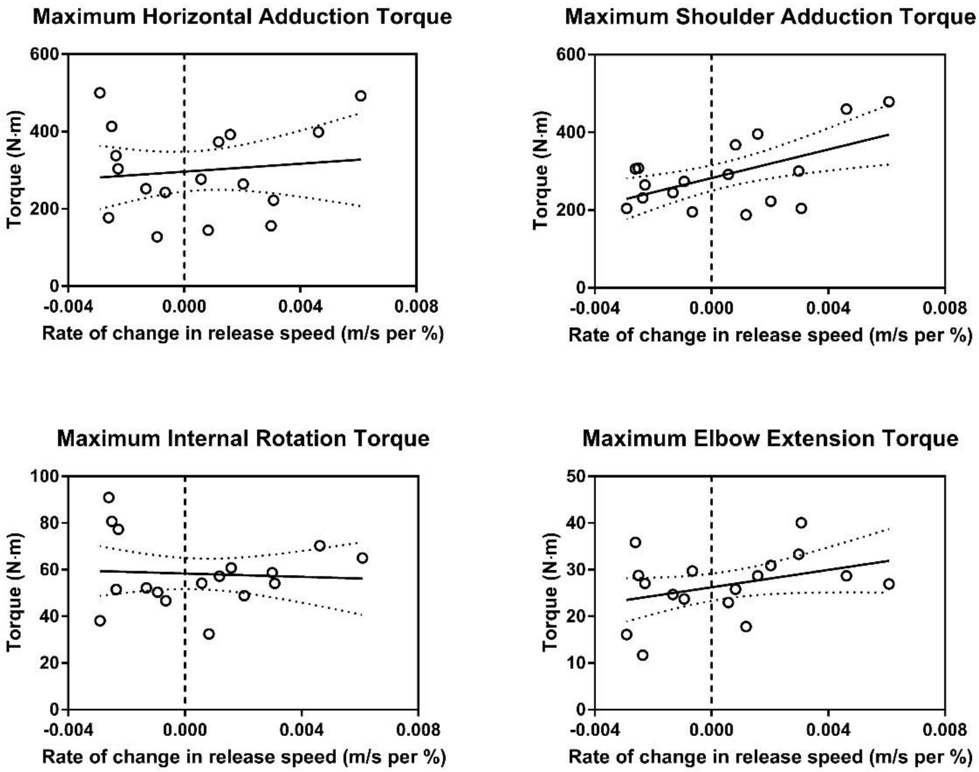

Figure 5-9: *Maximum joint torques for each throw performed without additional upper arm mass in relation to the rate of change in ball release speed with increasing upper arm mass. No strong correlations were observed.*

5.3.2. Experimental throws

5.3.2.1. Ball release speed

The best fit to the effect of additional upper arm mass on the ball release speed was an inverted u-shape for Participants 2, 3, and 6, and a straight line for Participants 1, 4, and 5 (Figure 5-10 and Table 5-6). The 95% CI of the gradient for Participants 1, 4, and 5 included zero, thus the additional upper arm mass did not affect the ball release speed of these participants.

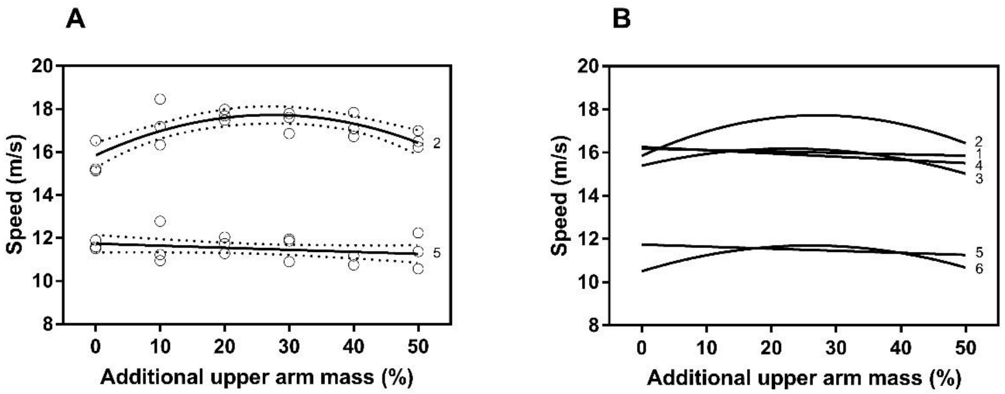

Figure 5-10: Changes in ball release speed in relation to additional upper arm mass. ***A*** *Representative data for Participant 2 and Participant 5, with the solid line representing the best fit model and the dashed lines representing the 95% CI.* ***B*** *Best fit models for all six participants. The ball release speed of three participants was not affected by additional upper arm mass (Participants 1, 4, 5), and three participants maximised their ball release speed with their optimal additional upper arm mass (Participants 2, 3, 6).*

The optimal added upper arm mass for Participants 2, 3, and 6 was around 25%. Participant 2 increased the ball release speed by 1.9 m/s from the throws performed without additional upper arm mass to the throws performed with the optimal upper arm mass. Participant 3 and Participant 6 achieved an increase in ball release speed of 0.8 m/s and 1.2 m/s respectively.

Table 5-6: Data for the linear fit and u-shape fit for the ball release speed of every participant and the probability of best fit of each model using AIC. The models with the highest probability to best fit the data are presented in bold.

	Linear Fit			U-shape			
Participant	**Gradient ± 95% CI**	**Yintercept**	**%***	**c**	**X_M ± 95% CI**	**Y_M**	**%***
1	**-0.007 ± 0.016**	**16.2**	**83.9**	-0.0001	0.0 ± ∞	16.1	16.1
2	0.012 ± 0.026	16.7	0.5	**-0.0025**	**27.3 ± 4.6**	**17.7**	**99.5**
3	-0.007 ± 0.028	15.9	13.3	**-0.0015**	**22.6 ± 10.7**	**16.2**	**86.7**
4	**-0.015 ± 0.016**	**16.3**	**69.3**	-0.0011	18.3 ± ∞	16.3	30.7
5	**-0.010 ± 0.026**	**11.7**	**84.5**	-0.0001	0.0 ± ∞	11.7	15.5
6	0.004 ± 0.021	11.1	21.1	**-0.0018**	**26.0 ± 13.7**	**11.7**	**78.9**

X_M=Optimal upper arm mass; Y_M=Maximum ball release speed
*Probability of either the straight line or inverted u-shape to best fit the data.

5.3.2.2. Maximum joint angles

No consistent pattern was observed for the maximum joint angles with changes in upper arm mass (Figure 5-11). Furthermore, similar effects on maximum joint angles were observed between the participants that increased their ball release speed and those that were not affected by additional upper arm mass. However, the participants that benefited from additional upper arm mass to maximise their ball release speed reached a greater maximum external shoulder rotation angle compared to the participants whose ball release speed was not affected.

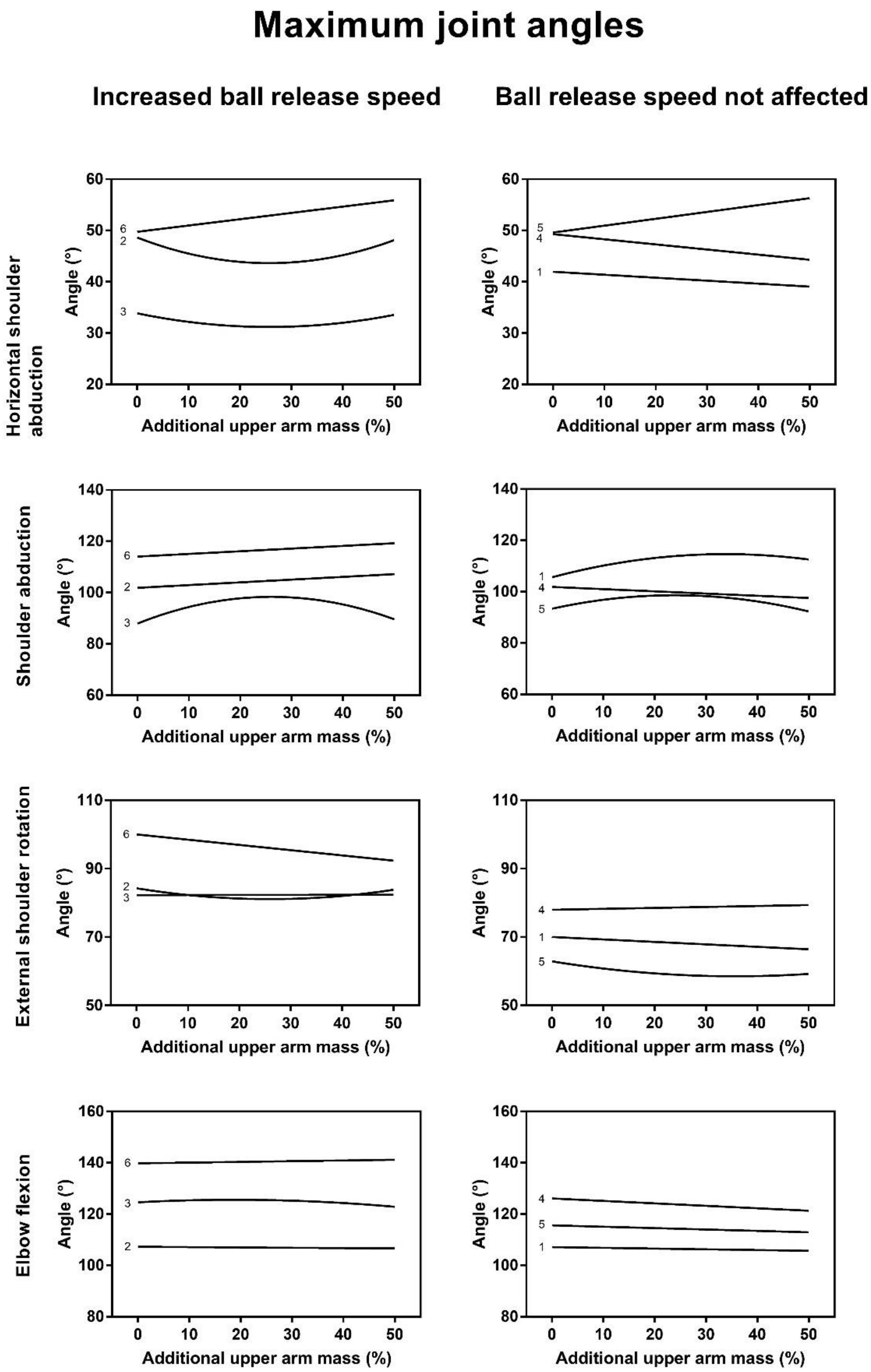

Figure 5-11: Maximum joint angles reached with additional upper arm mass for each participant that increased their ball release speed with a heavier upper arm mass (left) and the participants that were not affected by changes in upper arm mass (right). Each participant's maximum joint angles reacted differently to changes in upper arm mass.

5.3.2.3. Joint angles at the instant of ball release

No consistent pattern of how additional upper arm mass affected joint angles at the instant of ball release was observed (Figure 5-12). Even though some of the joint angles at the instant of ball release changed in a similar way for some participants, the throws resulted in a different effect on ball release speed.

5.3.2.4. Maximum joint angular velocities

Similar effects on the maximum joint angular velocities were observed between the participants that increased their ball release speed with additional upper arm mass and the participants that did not increase their ball release speed with additional upper arm mass (Figure 5-13). However, it is noticeable that the participant who generated the highest internal shoulder rotation angular velocity (Participant 2) managed to reach the same internal shoulder rotation angular velocity irrespective of the upper arm mass. Participant 2 increased ball release speed through increasing shoulder adduction angular velocity.

5.3.2.5. Maximum joint torques

No consistent pattern of the effect of additional upper arm mass on maximum joint torques was observed (Figure 5-14). Participant 3 was the only participant that generated higher maximum horizontal shoulder adduction torque with heavier upper arm masses, whereas the remaining participants produced less maximum horizontal shoulder adduction torque as the upper arm mass increased.

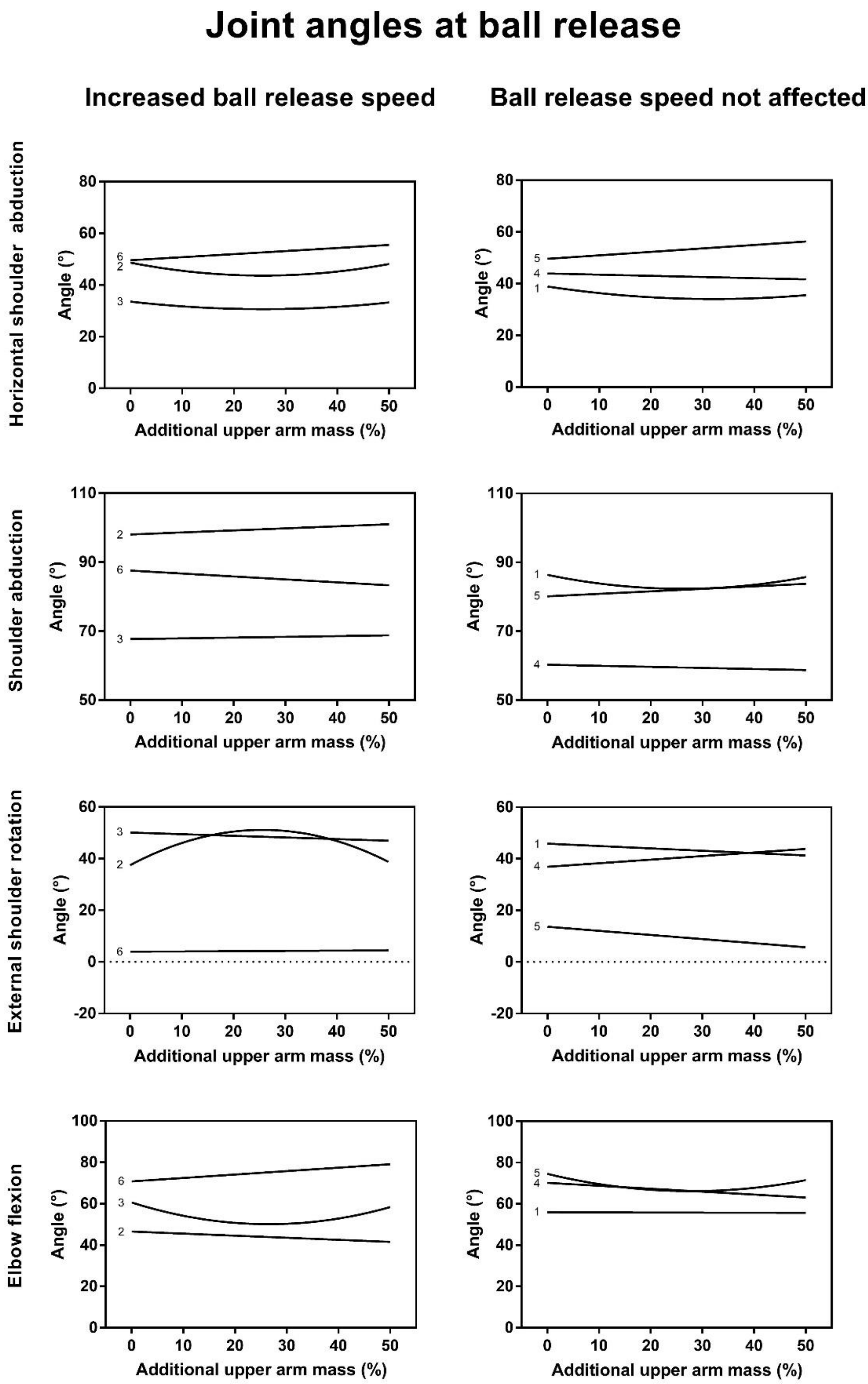

Figure 5-12: Joint angles at the instant of ball release with different amounts of additional upper arm mass for the participants that benefited from additional upper arm mass (left) and those that were not affected (right). Each participant's joint angles reacted differently to additional upper arm mass.

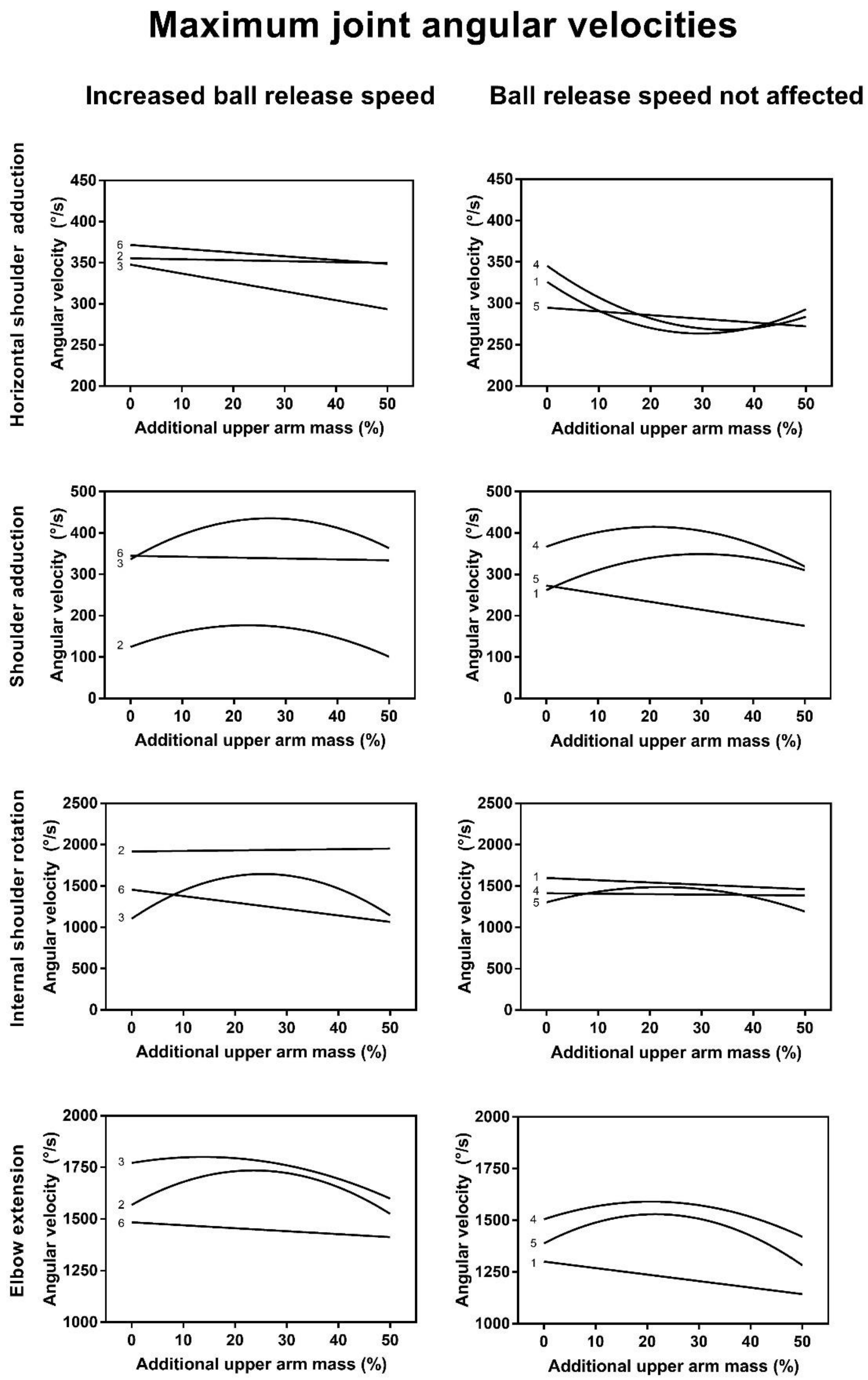

Figure 5-13: Maximum joint angular velocities with additional upper arm mass. Each participant reacted differently to additional upper arm mass.

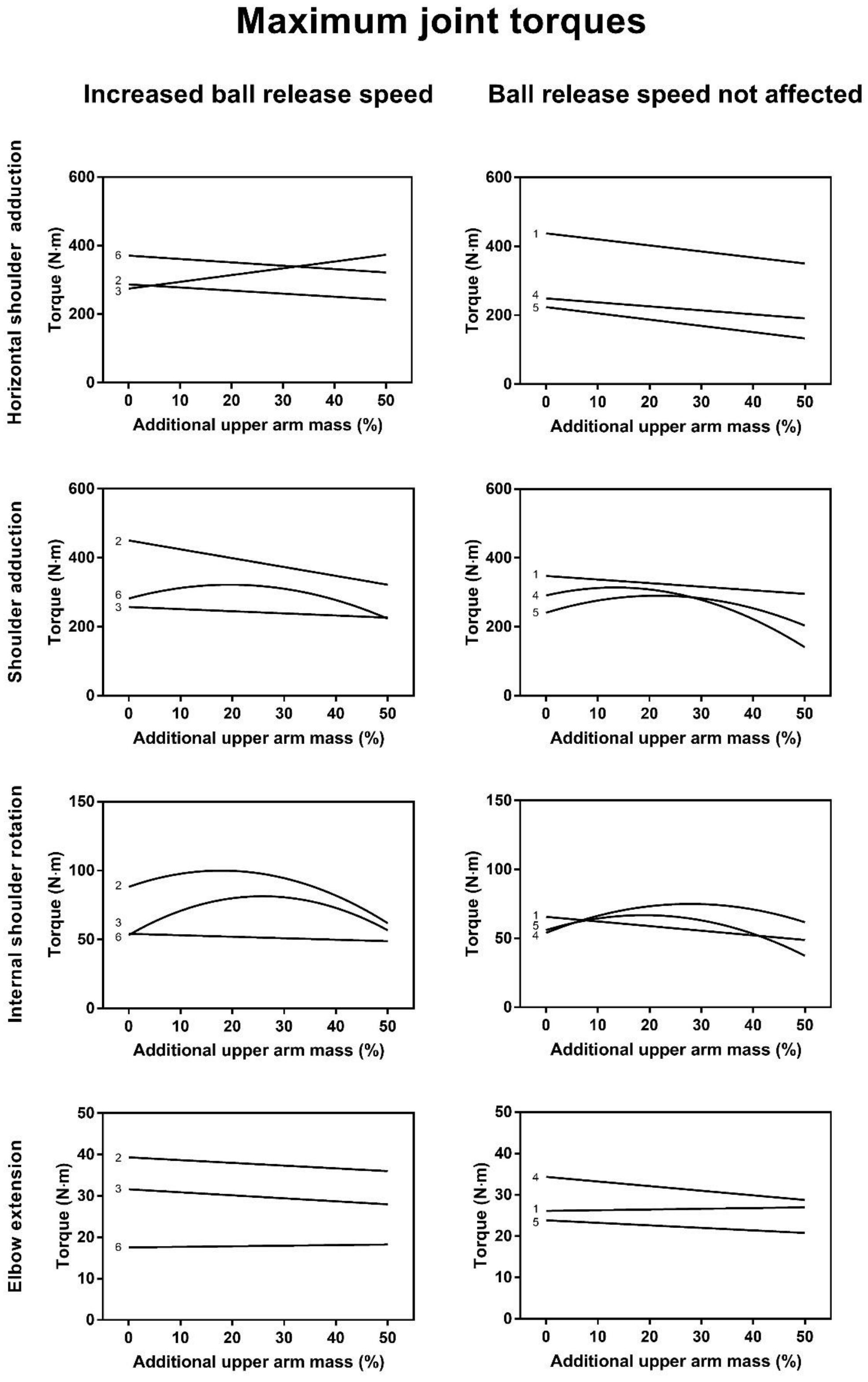

Figure 5-14: Maximum joint torques generated with additional mass attached to the participants' upper arm. Additional upper arm mass had the largest effect on maximum shoulder adduction torque and maximum internal shoulder rotation torque.

5.3.2.6. Optimal upper arm mass

Comparing the optimal upper arm mass of each kinematic and kinetic variable highlights that each participant’s throwing technique was affected in a different way by a heavier upper arm mass (Figure 5-15). As no consistent pattern was observed, no variable could be identified that affects the outcome of additional upper arm on overarm throwing.

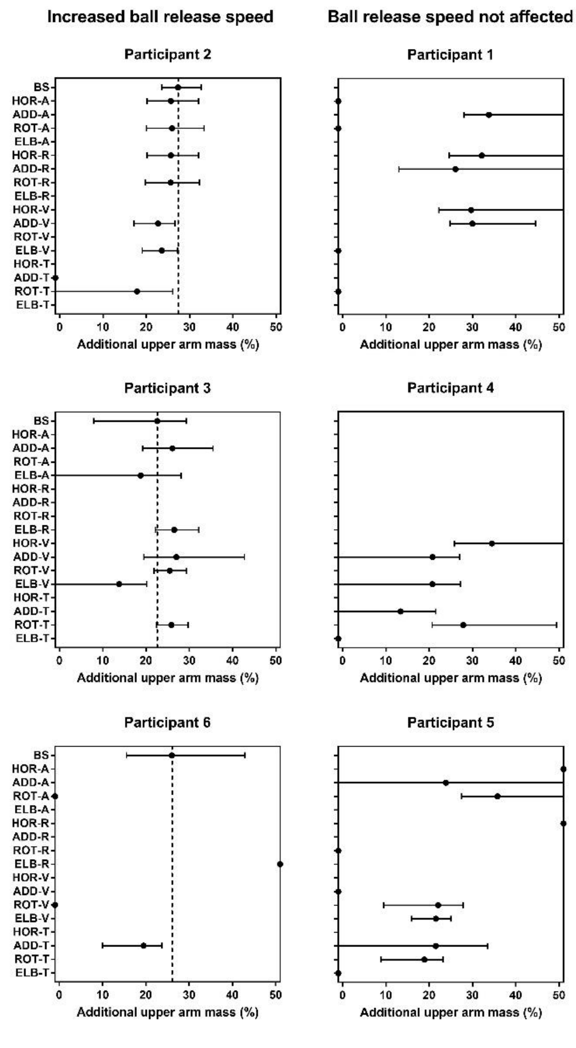

Figure 5-15: Mean and 95% CI of upper arm mass that resulted in a maximum or minimum for each variable analysed. The dashed vertical line represents the optimal upper arm mass. BS: Ball speed (m/s); HOR: Horizontal adduction; ADD: Shoulder adduction; ROT: Internal/external rotation; ELB: Elbow flexion. A: Maximum angle (°); R: Angle at release (°); V: Angular velocity (°/s); T: Torque (N·m).

5.4. Discussion

The results of the present study suggest that not every athlete would benefit from a heavier upper arm mass. In both the simulated throws and the experimental throws, adding mass to the upper arm did not have a consistent effect on all six participants. The simulated throws whose maximum internal shoulder rotation angular velocity and maximum elbow extension angular velocity were less affected by additional upper arm mass produced a higher ball release speed. The analysis of kinematic and kinetic variables did not provide a clear indication about why some participants had an optimal upper arm mass that maximised their ball release speed and some participants did not.

In the present study, a mix of both experimental and simulation approach was used to determine an athlete's optimal upper arm mass that results in the highest ball release velocity. The aim of such an approach was to provide a tool for coaches and athletes to identify the athlete's optimal upper arm mass. However, as there were substantial differences between the experimental and simulation results, the method employed in the present study might not have been adequate to reach this aim. Therefore, further work might be required in order to improve the model used in the present study.

5.4.1. Ball release speed

5.4.1.1. Simulated throws

The best fit model to the ball release speed of the simulated throws with additional upper arm mass was a straight line for the majority of the throws, which means that an optimal upper arm mass within the range of masses tested could not be identified. Even though Linthorne et al. (n.d.) observed an optimal upper arm mass while testing similar upper arm masses in a javelin throw, the results of the simulations performed in the present study did not agree with those findings. However, the results from the present study confirm the findings of the two-dimensional simulations performed in my first study (Chapter 3), which suggests that the optimal upper arm mass is heavier than the masses tested in the present study. Furthermore, the results from the present study also agree with the findings of Chapter 4 as the effect of additional upper arm mass varied between throws. The differences in optimal upper arm mass between the throws performed in the present study and in the javelin throwing study by Linthorne et al. (n.d.) might be caused by differences in throwing technique. However, further studies are required to determine how additional upper arm mass affects throwing performance in different sports.

The largest increase in ball release speed recorded in the present study was 0.30 m/s, and the largest decrease in ball release speed in the simulated throws was 0.15 m/s. Petersen et al. (2004) suggested that in cricket bowling the smallest change in ball release speed that a batsman would notice is about 0.70 m/s. Therefore, in the present study none of the simulated throws would substantially affect the performance of a throwing athlete. However, it remains to be seen if heavier upper arm masses would have had a larger effect on the ball release speed of the simulated throws.

5.4.1.2. Experimental throws

Similar to the results obtained from the simulated throws, the participants in the experimental throws reacted in different ways when they performed throws with additional mass attached to their upper arm. Three out of the six participants displayed an optimal upper arm mass that maximises their ball release speed, whereas a heavier upper arm mass did not affect the ball release speed of the other three participants. In the present study, the maximum increase in ball release speed recorded with the optimal upper arm mass was 1.9 m/s. The other two participants increased their ball release speed by 1.2 m/s and 0.8 m/s. The increase in ball release speed by all three participants was higher than the value previously mentioned to make a noticeable difference to the outcome in cricket fast bowling (0.7 m/s) (Petersen et al., 2004). These results confirm the findings of previous studies, that some athletes can benefit from optimising their upper arm mass in order to improve their throwing performance (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998; Chapter 3 & 4).

The optimal upper arm masses recorded in the present study are similar to those found in the study by Linthorne et al. (n.d.), but considerably less than the optimal upper arm mass found in Chapter 3. The study by Southard (1998) recorded an increase in ball release by less skilled throwers with even heavier masses attached to the upper arm. On average 1.4 kg was attached to the participant's upper arm in that study, which is higher than the heaviest mass used in the present study (1.12 kg). The findings by Southard (1998) suggest that the optimal upper arm mass of some athletes could be heavier than the range of masses tested in my studies.

5.4.1.3. Comparison between simulated and experimental throws

The model used in the present study to simulate the effect of additional upper arm mass on throwing performance did not predict the athlete's optimal upper arm mass. The experimental throws showed that some athletes could maximise their ball release speed with optimal upper arm mass. However, not every participant that took part in the present study benefited from a heavier upper arm mass to increase their ball release speed. As the range of masses tested in the present study was considerably less than the optimal upper arm mass identified in my first study (Chapter 3), the optimal upper arm mass for some of the participants might be above the heaviest amount tested and simulated in the present study. The outcome of both the simulated and experimental throws highlight the challenges that athletes and coaches face when attempting to determine an athlete's optimal upper arm mass. The varying results of additional upper arm mass on ball release speed in overarm throwing between participants and between the simulation and experimental data show that further research is required in order to determine an athlete's optimal upper arm mass.

5.4.2. Throwing mechanics

5.4.2.1. Simulated throws

Attaching additional mass to the upper arm had only small effects on the participant's ball release speed. However, analysing the changes in joint angular velocity highlighted that increasing the upper arm mass had a negative effect on the internal shoulder rotation angular velocity for the majority of the sets of throws. Only three sets of throws out of the seventeen used for simulation generated higher internal shoulder rotation angular velocity with a 50% increase in upper arm mass. However, analysing the relation between the changes in internal shoulder rotation angular velocity and the rate of change in ball release speed with increasing upper arm mass revealed that the throws where a heavier upper arm mass had less effect on the internal shoulder angular velocity had a greater ball release speed. This finding might be relevant to baseball pitchers, who produce internal shoulder rotation angular velocities of up to 10,000°/s (Werner et al., 2001) and rely on the internal shoulder rotation to achieve a high ball release speed. Therefore, if a baseball pitcher should attempt to optimise their upper arm mass, it is crucial that the changes in inertial parameters do not limit their ability to generate the same values of internal shoulder rotation angular velocity.

Further evidence of the importance of maintaining a high internal shoulder rotation angular velocity irrespective of the upper arm mass was provided by the differences in elbow extension angular velocity between simulated throws with a heavier upper arm mass and throws performed without additional upper arm mass. The throws that increased the ball release speed with additional upper arm mass did so by increasing the elbow extension angular velocity or generating similar elbow extension angular velocities irrespective of the upper arm mass. Hirashima et al. (2007) showed that the elbow extension in overarm throwing is mainly produced by interaction torques generated through the movement of the heavier proximal joints. Therefore, retaining similar values of internal shoulder rotation angular velocity with a heavier upper arm mass should also increase the elbow extension angular velocity. However, it has to be noted that one outlier occurred that had a substantial increase in elbow extension angular velocity, even though the ball release speed of that throw decreased. Further analysis is required to determine why the ball release speed in that throw was negatively affected.

The effect that additional upper arm mass has on the shoulder rotation angular velocities suggests that the throws that generated similar values of maximum shoulder angular velocities had an increase in elbow extension angular velocity and an increase in ball release speed. Thus, the results suggest that athletes could benefit from optimising their upper arm mass as long as they are able to generate the same amount of shoulder angular velocity. Through increasing the upper arm mass, athletes could improve the efficiency of transfer of energy between the upper arm and forearm, resulting in a higher ball release speed. Further analysis focussing on the changes of interaction torques with increasing upper arm mass could provide vital information about how inertial parameters of a body segment affect the movement and position of the other segments in overarm throwing.

Throws performed with a greater maximum horizontal shoulder abduction angle were negatively affected by increasing upper arm mass. The remaining kinematic and kinetic variables were similar between the throws, irrespective of the rate of change in ball release speed with increasing upper arm mass. These results highlight that small differences in throwing technique between participants or within a participant can change the effect of additional upper arm mass on ball release speed, which makes it difficult to determine an athlete's optimal upper arm mass. Thus, athletes should only optimise their upper arm mass if they are able to consistently reach higher ball release speeds with a heavier upper arm mass. Therefore, further analysis is required to analyse the effect of additional upper arm mass on highly skilled throwers, and preferably under similar conditions to competition.

5.4.2.2. Experimental throws

Kinematic and kinetic analysis of the throws performed with changes in upper arm mass did not reveal a consistent pattern of how upper arm mass affects an athlete's throwing mechanics. In overarm throwing the position and the movement of one segment is determined by the joint torques and by the position and the movement of other joints (Hirashima et al., 2008) and so changes in upper arm mass could affect each throw in a different way. Therefore, the results of the present study suggest that before coaches attempt to optimise an athlete's upper arm mass, it has to be ensured that the change results in a substantial increase in ball release speed and that the throws performed with a heavier upper arm mass do not result in higher loads on the shoulder joint or elbow joint (Chapter 4).

5.4.2.3. Mechanisms that affect an athlete's optimal upper arm mass

The results of the present study did not identify the kinematic or kinetic variables in an athlete's throwing technique that predict if an athlete could benefit from a heavier upper arm mass. Even though the results of the simulated throws suggested that throwers that reduced the maximum horizontal shoulder abduction angle could benefit from additional upper arm mass, no such evidence was observed during the throwing experiment. Furthermore, the results of the simulations highlight that athletes than can maintain the same level of shoulder angular velocity with a heavier upper arm mass were able to benefit from an increase in angular velocity at the distal segments through a more efficient transfer of energy (Fortenbaugh &

Fleisig, 2009). However, no such evidence was observed in the present study for throws performed with additional upper arm mass, as a similar effect on both shoulder and elbow angular velocities were recorded between the participants, irrespective of their performance.

5.4.3. Limitations

The participants in the present study were not highly skilled athletes and were asked to perform an unusual throwing motion. It remains to be seen if the same outcomes will be observed with highly skilled throwers. Therefore, due to the lack of throwing experience of the participants in the present study, the findings might not apply to athletes from any specific sport.

The present study did not analyse the effect that additional upper arm mass has on the accuracy of a throw. In some throwing sports, accuracy is crucial for performance as the athletes have to aim towards a target (Freeston et al., 2015; Freeston & Rooney, 2014; Hore, Watts, Martin, & Miller, 1995) or release the projectile at the optimal release angle in order to maximise the distance thrown (Linthorne, 2001; Linthorne & Everett, 2006; Linthorne & Stokes, 2014). Furthermore, as the timing of ball release can also affect the ball release speed, especially in unskilled throwers (Jegede, Watts, Stitt, & Hore, 2005), future research should record the athlete's ability to accurately release the projectile when analysing the effect of additional upper arm mass on throwing performance.

Another limitation of the present study was the lack of subject-specific segmental inertial parameters to determine the participant's upper arm mass. Future studies that attempt to determine an athlete's optimal upper arm mass should use a more accurate method to determine the participant’s upper arm mass, which would affect the optimal upper arm mass as well as the computer models used to analyse and simulate the movement.

5.4.4. Applications

The results of the present study did not identify kinematic or kinetic characteristics that determine how additional upper arm mass affects an athlete’s throwing performance. However, the present study is further evidence that some athletes could benefit from increasing their upper arm in order to reach higher ball release speeds (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998; Chapter 3 & 4). Furthermore, the results of the simulations suggest that if athletes are able to maintain or even increase their internal shoulder angular velocity with a heavier upper arm mass they are more likely to reach higher ball release speeds. Therefore, an athlete’s throwing mechanics with additional upper arm mass should be analysed first before attempting to increase an athlete’s upper arm muscle mass in order to maximise performance without increasing the risk of injuries (Fortenbaugh et al., 2009).

5.4.5. Further work

The results of the throw simulations provided some evidence that the throws that resulted in a higher ball release speed with additional upper arm mass benefited from the increase in angular momentum due to the heavier mass and as a result affected the elbow extension angular velocity. However, further analysis is required to identify how a heavier upper arm mass affects the movement of the distal segments, for example through the analysis of interaction torques (Hirashima, Kudo,

& Ohtsuki, 2007; Hirashima, Kudo, Watarai, et al., 2007). As the present study did not identify a kinematic or kinetic variable that determines the effect of additional upper arm mass on ball release speed, analysing how one segment determines the movement of another segment could help to explain why certain participants increase their ball release speed and some do not.

Furthermore, as the participants in the present study did not participate in a sport that requires throwing on a regular basis, the findings cannot be applied to highly skilled throwers. Further work is required to analyse the effect of additional upper arm mass on highly skilled athletes of various sports throwing projectiles of various masses. Linthorne et al. (n.d.) observed an optimal upper arm mass in a javelin throw, but further research is required to determine if the same principle can be applied in sports such as baseball, cricket, or handball. Furthermore, different throwing techniques within a sport could be analysed in order to determine which athletes can benefit from optimising their upper arm mass (Fleisig et al., 2006; Wagner et al., 2010). Southard (1998) suggested that skilled throwers might not benefit from additional upper arm mass. Furthermore, the higher upper arm muscle volume in baseball pitcher's dominant upper arm might indicate that highly skilled throwers have reached their optimal upper arm mass already (Yamada, Yamashita, et al., 2013; Yamada, Masuo, et al., 2013).

Future studies should also include throwing accuracy when analysing the effect of additional upper arm mass on throwing performance. As the accuracy of ball release can affect the ball release speed of less skilled throwers (Jegede et al., 2005), further research is required in order to determine if an athlete's accuracy of ball release is affected by a heavier upper arm mass. As the central nervous system is able to compensate for changes occurring during overarm throwing in order to control ball release (Hore et al., 2001), it remains to be seen if the central nervous system compensates for changes in inertial parameters so as to retain the accuracy of ball release.

5.5. Conclusions

The present study is further evidence that some athletes could benefit from a heavier upper arm mass in order to maximise their ball release speed. However, as previous studies already identified, this might not be the case for every athlete involved in a throwing sport (Southard, 1998; Chapter 4). The methods used in the present study did not allow me to accurately predict the effect of additional upper arm mass on the ball release speed of the participants, but the throw simulations provided some insight into the importance of maintaining a high shoulder angular velocity in order to increase ball release speed with a heavier upper arm mass. Thus, athletes whose shoulder angular velocities are not affected by additional upper arm mass should be able to benefit from a heavier upper arm mass. Furthermore, the results of the throwing experiment highlight that there is no consistent pattern of how additional upper arm mass affects an athlete's throwing mechanics, which further supports previous findings that each athlete's individual optimal upper arm mass would have to be determine in order to maximise ball release speed (Linthorne et al., n.d.; Chapter 3 & 4).

Chapter 6: General Discussion

In sports that involve throwing a projectile (such as baseball, cricket, and some of the field events in athletics), the aim is to throw either as fast or as far as possible. Therefore, increasing the release velocity of the projectile is the main interest of athletes as this variable has the greatest effect on throwing performance (Linthorne & Stokes, 2014). Most research in the biomechanics of throwing has focused on describing the throwing motion (Dillman et al., 1993; Werner et al., 1993), identifying variables that allow athletes to throw faster (Gray et al., 2006; Kageyama et al., 2015; Matsuo et al., 2001; Werner et al., 2008) or analysing different training programs (DeRenne, Ho, & Murphy, 2001; Marques et al., 2012; van den Tillaar, 2004). The effect that changes in arm segment masses have on ball release speed in overarm throwing has not attracted much interest from researchers so far.

The results from a few studies suggest that athletes can benefit from increasing the mass of their upper arm to achieve a higher ball release speed (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998). These findings imply that there is an optimal upper arm mass that results in the best throwing performance, as has been shown in a modified javelin throw (Linthorne et al., n.d.). However, no previous study has determined the optimal upper arm mass that produces the highest ball release speed. Also, the effect of additional upper arm mass on joint kinematic variables and joint kinetic variables is still not known, and thus it remains to be seen if a heavier upper arm mass causes kinematic changes that increase the risk of injuries.

Therefore, the main aim of this series of studies was to determine the optimal combination of arm segment masses that result in the highest ball release speed in overarm throwing. Even though previous studies have shown that a heavier upper arm mass can result in a higher ball release speed (Kim et al., 2008; Linthorne et al., n.d.; Southard, 1998), none of these studies identified how changes in upper arm mass affect joint kinematics and joint kinetics. Therefore, analysis of the throwing motion could provide vital information about how a heavier upper arm mass affects throwing performance and throwing mechanics.

6.1. Summary of main findings

6.1.1. Chapter 3

In the first study, a two-dimensional computer simulation model was to determine the optimal arm segment masses that maximises ball release speed. The results of the simulations showed that there is an optimal upper arm mass. However, this optimum depends on the forearm mass and on the shoulder torque used to drive the model. As the forearm mass in the simulation model was increased, the optimum upper arm mass also increased. Changing the forearm mass showed that the lower the forearm mass the higher the ball release speed. Furthermore, increasing the shoulder torque produced a higher ball release speed and a slightly lower optimal upper arm mass.

These findings suggest that athletes could benefit from optimising their upper arm mass in order to maximise their ball release speed. Furthermore, if athletes are able to keep their forearm mass as low as possible and increase their shoulder torque, their optimal upper arm mass should be lower, thus making it easier for them to reach their optimal upper arm mass through hypertrophy exercise. Even though the optimal segment masses identified by the two-dimensional throwing model are not realistic for athletes to achieve (forearm: 0.5 kg or even lower; upper arm: more than double the mass of an average adult male), this study provides some vital information about how the upper arm mass and forearm mass affect ball release speed. Furthermore, these findings were a first step towards determining the optimal upper arm mass in overarm throwing that produces the highest ball release speed.

6.1.2. Chapter 4

The second study analysed the changes in joint kinematic, joint kinetic, and temporal variables with additional mass attached to the participant's upper arm. The aim of this study was to determine how heavier upper arm masses affect throwing mechanics and the risk of injury. Even though the majority of participants showed a clear optimal upper arm mass if analysed individually, no common optimal upper arm mass could be determined. The optimum upper arm mass varied between participants, ranging from 7.2% to 26.9% increase in upper arm mass, and resulted in an increase in ball release speed that ranged from 0.04 m/s to 2.40 m/s.

Analysis of changes in throwing mechanics with additional upper arm mass revealed that most variables did not change much between the different mass conditions. The only variables that were affected were the maximum external shoulder rotation angle, maximum shoulder adduction angular velocity and maximum shoulder compression force. All remaining variables were not substantially different between the mass conditions. These results showed that increasing the upper arm mass does not substantially change the athlete's throwing mechanics, and, as a consequence, does not increase the risk of injuries in overarm throwing. The findings of this study highlight that the concept of optimising an athlete's upper arm mass could be used in throwing sports.

6.1.3. Chapter 5

The main aim of the third study was to predict the participant's optimal upper arm mass and to identify the joint kinematic variables and joint kinetic variables that determine the athlete's optimal upper arm mass. This study was divided into two parts. First, a three-dimensional model of the arm segments was used to simulate the effect of changes in upper arm mass, driven by joint torque profiles recorded from the participants. In the second part, the simulated throws were compared to throws performed by the participants with a series of masses attached to their upper arm mass.

Even though the ball release of the simulated throws varied compared to the throws recorded in the throwing experiment, both methods confirmed that a heavier upper arm does not necessarily result in a higher ball release speed. Whereas some participants showed a clear optimal upper arm mass (ranging from 22.6% to 27.3% of additional mass attached to the participant's upper arm), only small variations in ball release speed were observed in the simulated throws as the upper arm mass was increased. The participants that benefited from optimising their upper arm mass increased their ball release speed by about 1.3 m/s, which is an increase by about 9.5% from the throws performed without additional upper arm mass.

Analysis of changes in joint angular velocities of the throws simulated with additional upper arm mass revealed that athletes could benefit from a heavier upper arm as long as the changes in inertial parameters do not restrict their ability to generate a high internal shoulder rotation angular velocity. Reductions in internal shoulder rotation angular velocities with heavier upper arm mass caused a decrease in elbow extension angular velocity and a lower ball release speed. Furthermore, the throws whose internal shoulder rotation angular velocity was less effected had an increase in elbow extension angular velocity and a higher ball release speed. These findings suggest that a heavier upper arm optimised the transfer of angular momentum between the body segments. However, this study could not identify any common kinematic or kinetic characteristics of an athlete's throwing mechanics that could allow athletes to determine if they would benefit from a higher optimal upper arm mass.

6.2. Limitations

A limitation of the current project was the skill level of the participants. Due to limited access to highly skilled throwers, all participants were physically active adults who were free of shoulder injuries and did not regularly participate in any sporting activity that required them to throw a projectile at maximum velocity. Therefore, the findings of this project cannot be applied to highly skilled throwers and further research is required to determine if highly skilled throwers react in the same way as was observed in these studies. Furthermore, the throws analysed in this project were not sport-specific.

Another limitation was the simplified shoulder model used in Chapter 4. The shoulder complex was reduced to a single joint, the glenohumeral joint. This method is used in the majority of throwing-related studies (Fleisig et al., 1996; Hirashima, Kudo, Watarai, et al., 2007; Hong et al., 2001; Hore et al., 2011; Keeley et al., 2012; Roach & Lieberman, 2014) due to the difficulties in tracking the scapula movement (Veeger et al., 2003). A recent study on Dutch baseball pitchers managed to analyse overarm throwing with a more accurate shoulder model (Gasparutto et al., 2015). Future research on overarm throwing should therefore use shoulder models that allow movement about all three joints.

Another limitation of the current project was the estimation of the participant's upper arm mass using data by de Leva (1996). This method estimates the body segment mass from the total body mass, I decided to use this method as an athlete's upper arm mass can quickly be determined at the beginning of data collection. Even though there are more accurate methods available (Furlong, 2010), the majority are more time-consuming. However, future research should use a more accurate method to determine the participant's arm segment masses.

6.3. Applications

The main aim of the present project was to determine the athlete's optimal upper arm mass that results in the highest ball release speed in overarm throwing. The findings of the three studies confirm that some athletes could benefit from increasing their upper arm mass in order to optimise the transfer of angular momentum between the arm segments. However, as the optimal upper arm mass varied between participants and not every participant benefited from additional upper arm mass, it is crucial for coaches to identify an athlete's optimal upper arm mass in order to avoid the heavier upper arm mass having a negative effect on performance or increase the risk of injury.

The simulations performed in Chapter 5 suggest that an athlete that is able to generate a similar internal shoulder rotation angular velocity with a heavier upper arm mass should benefit from increasing their upper arm mass. This finding implies that future training programs could focus on increasing upper arm muscle mass through strength training and combining it with throwing-specific training that emphasises the generation of a high internal shoulder rotation angular velocity. However, further research is required in order to design sport-specific training programs that aim to optimise an athlete's upper arm mass.

6.4. Further Work

Southard (1998) observed an increase in ball release speed in overarm throwing with additional mass attached to the participant's upper arm. Even though his findings suggest that athletes could employ this concept in order to improve their performance, this area of research has attracted very limited attention so far. Apart from the current project, only the studies by Kim et al. (2008) and Linthorne et al. (n.d.) have focussed on optimising the athlete's upper arm mass. However, there are still many questions that future research could focus on.

First of all, more research is required with highly skilled throwers in order to see if they could benefit from a heavier upper arm mass or if they have already reached their optimal upper arm mass through their training routine. As baseball pitchers have a higher upper arm muscle volume compared to athletes from other sports (Yamada, Yamashita, et al., 2013; Yamada, Masuo, et al., 2013), it remains to be seen if they can further increase their ball release speed.

Further work is also required to analyse how changes in upper arm mass affect an athlete's ability to accurately release the ball and what affect their timing of ball release has on ball release speed (Jegede et al., 2005). Previous studies found that interaction torques act on the wrist joint in order to control ball release

(Hirashima et al., 2003). Therefore, future research could quantify the interaction torques in order to determine how they are affected by additional upper arm mass.

In order for throwing athletes to benefit from the current findings, training programs would have to be tested that include hypertrophy exercise focussing on increasing the athlete's upper arm mass. As such an intervention would also affect muscle strength, it could be challenging to determine if improvements in throwing performance are cause by the heavier upper arm mass or by the increased muscle strength.

6.5. Conclusions

The current project provides further evidence that some athletes can benefit from increasing their upper arm mass in order to increase their ball release speed in overarm throwing. The optimal upper arm mass varies between athletes and depends on the forearm mass and the skill level of the athlete. Furthermore, the results of the present project suggest that a heavier upper arm mass does not substantially increase the loads on the shoulder joint and elbow joint, and thus there is no evidence in the current project that a heavier upper arm mass increases the risk of injury. However, as an increase in ball release speed with a heavier upper arm mass could not be observed for every participant in the present project, athletes should be cautious when attempting to optimise their upper arm mass.

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Appendices

Appendix 1: Calculating Akaike's Information Criterion (AIC)

Akaike's Information Criterion is a method of comparing the fit of two models to a set of data points (Motulsky & Christopoulos, 2003). This method quantifies how much more likely one model fits the data compared to the other model. In order to calculate which model fits the data better, an information criterion (AIC) is calculated:

$$AIC = N \cdot ln\left(\frac{SS}{N}\right) + 2K$$

where N is the number of data points, K is the number of parameters fit by the regression plus one, and SS is the sum of the square of the vertical distances of the points from the curve.

However, with a low number of data points, it is recommended to use a corrected AIC value:

$$AIC_c = AIC + \frac{2K(K+1)}{N-K-1}$$

Comparing the AIC (or corrected AIC) values obtained for each model provides information about which of the two models fits the data better. The model with the lowest AIC value is the most likely to be correct. In order to quantify how much more likely one model fits the data better compared to the other, we can calculate the probability:

$$\Delta AIC = AIC_B - AIC_A$$

$$probability = \frac{e^{-0.5\Delta}}{1 + e^{-0.5\Delta}}$$

This method only provides information about which one of the two models tested is a better fit. The method does not exclude that a different model could be even better.

Appendix 2: Ethics Approval

Head of School of Sport & Education
Professor Ian Rivers

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Patrick Fasbender
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6th August 2014

Dear Patrick

RE75-13 The effect of changes in arm mass distribution on the throwing motion

I am writing to confirm the Research Ethics Committee of the School of Sport and Education received your application connected to the above mentioned research study. Your application has been independently reviewed to ensure it complies with the University/School Research Ethics requirements and guidelines.

The Chair, acting under delegated authority, is satisfied with the decision reached by the independent reviewers and is pleased to confirm there is no objection on ethical grounds to grant ethics approval to the proposed study.

Any changes to the protocol contained within your application and any unforeseen ethical issues which arise during the conduct of your study must be notified to the Research Ethics Committee for review.

On behalf of the Research Ethics Committee for the School of Sport and Education, I wish you every success with your study.

Yours sincerely

PP Dr Richard J Godfrey
Chair of Research Ethics Committee
School Of Sport and Education

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