2019

# The relationship between angular momentum of the lower trunk and shoulder joint forces in overarm throwing athletes

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# THE RELATIONSHIP BETWEEN ANGULAR MOMENTUM OF THE LOWER TRUNK AND SHOULDER JOINT FORCES IN OVERARM THROWING ATHLETES

A thesis submitted to
the Graduate College of
Marshall University
In partial fulfillment of
the requirements for the degree of
Master of Science
In
Biomechanics
by
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Approved by
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Marshall University
July 2019

## APPROVAL OF THESIS

We, the faculty supervising the work of Kevin Moore, affirm that the thesis, *The Relationship between Angular Momentum of the Lower Trunk and Shoulder Joint Forces in Overarm Throwing Athletes*, meets the high academic standards for original scholarship and creative work established by the Biomechanics Department and the College of Kinesiology. This work also conforms to the editorial standards of our discipline and the Graduate College of Marshall University. With our signatures, we approve the manuscript for publication.

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# ACKNOWLEDGMENTS

I want to thank all the people who helped me along the way.

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**ABSTRACT**

Overarm throwing athletes utilize the kinetic chain, which allows forces generated by the lower body to be transmitted to the throwing arm in a proximal-to-distal sequence. Efficient force transmission from the lower body to the throwing arm can improve performance and reduce risk for injury. The purpose of this thesis was to explore the relationship between the lower trunk (pelvis) maximum angular momentum and the joint resultant forces at the shoulder during the overarm throwing motion of baseball athletes. I hypothesized that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint anterior shear force at ball release, and that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint compressive force at ball release. Two high-speed video cameras were used to record twenty-four competitive male baseball players executing an overarm throw. The videos were digitized, and 3D landmark coordinates were obtained using the Direct Linear Transformation procedure. Lower trunk angular momentum, shoulder joint compressive force, and shoulder joint anterior shear force were calculated from the 3D landmark coordinates and anthropometric data. Bivariate correlations were computed to determine if an association existed between maximum lower trunk angular momentum and shoulder joint anterior shear force at release or shoulder joint compressive force at release. There was no association between lower trunk maximum angular momentum and shoulder joint anterior shear force ($r$ = 0.149, $p$ = 0.244). There was also no association between lower trunk maximum angular momentum and shoulder joint compressive force ($r$ = 0.222, $p$ = 0.149). The lack of association between the lower trunk maximum angular momentum and shoulder joint forces may indicate that this

relationship is not determinative of overarm throwing technique. An alternative explanation is that the subjects exhibited inefficient mechanics and an improper timing sequence of the kinetic chain. Future work should investigate the sequencing of force transmission between the lower body and upper body.

# CHAPTER 1

## INTRODUCTION

### Overarm Throwing Motion

Overarm throwing athletes try to optimize ball velocity while minimizing injury risk by moving efficiently. The overarm throwing motion is complex and involves movements of the entire body working in harmony. The overarm throwing motion is broken down into sequential phases to aid description and analysis. The phases are: the wind-up phase, the stride phase, the arm cocking phase, the arm acceleration phase, the arm deceleration phase, and the follow-through phase (Fleisig, Barrentine, Escamilla, & Andrews, 1996; Zheng, Fleisig, Barrentine, & Andrews, 2004; Rojas et al., 2009). Throughout these phases, forces generated by the body are transmitted to the ball by joint rotations made in a proximal-to-distal order known as the kinetic chain. The distal body segments transmit and add to the forces that were generated by the proximal body segments (Feltner & Dapena, 1989; Putnam, 1993). A great resultant force is applied to the ball at the most distal end of the kinetic chain, which causes the ball to accelerate. Maximizing the ball's release speed depends on efficient transmission and accumulation of force along the kinetic chain in the appropriate sequence.

Efficient force transmission throughout the phases of the overarm throwing motion is achieved by the transfer of momentum across segments. The force transmission process begins with the generation of a ground reaction force between the push-off foot and the ground (MacWilliams, Choi, Perezous, Chao, & McFarland, 1998). The push off foot directs this ground reaction force in the anterior direction where the landing foot then contacts the ground and supplements with additional ground reaction force. These transmitted ground reaction forces act on the lower extremities to increase their momentum (Alexander, 1991; MacWilliams et al., 1998; Young, Herring, Press, & Casazza, 1996). The lower trunk (pelvis) takes the anteriorly directed linear momentum and rotates about a superior-inferior axis which generates angular momentum (Young et al., 1996). A direct relationship exists between the change in angular momentum of the proximal body segment and the rotational force (torque) of the corresponding distal joint. Rapid elbow extension and ball velocity at release are due to the preceding movements of the upper arm and trunk segments (Feltner, 1989). Accelerations of the elbow and wrist are dependent on torques originally produced by the more proximal shoulder joint (Hirashima, Yamane, Nakamura, & Ohtsuki, 2008; Oliver, 2014). Greater shoulder torques are associated with trunk rotation and flexion movements (Hirashima et al., 2008; Marshall & Elliott, 2000; Oliver, 2014). To better understand the transmission of forces in the overarm throwing motion, we investigated the transfer of angular momentum from the lower trunk to the shoulder and the resulting joint torque and force. This transfer of angular momentum from the lower trunk to the shoulder is particularly relevant, because it is a fundamental link in the kinetic chain. Since angular momentum is a kinematic-based variable, the relationship between angular momentum of the lower trunk and the resultant joint torque at the shoulder can be explained to athletes in terms of how they move. Our findings, therefore, can provide practical information about the overarm throwing motion.

**Overarm Throwing Injuries**

Baseball athletes are at a high risk for injuries that have great social and economic costs, cause lost participation time, and hinder skill development. On average in Major League Baseball (MLB) from 1998 to 2015, 464 players which is 62% of the MLB, were placed on the disabled list due to injuries every year (Conte, Camp, & Dines, 2016). These injuries cost MLB approximately $423 million per year and a total of $7.6 billion over the span of 18 years (Conte et al., 2016). The majority of these injuries occur during practice or without contact with another player or the ground (Krajnik, Fogarty, Yard, & Comstock, 2010).

During the overarm throwing motion, the forces generated by the lower body must be transmitted, controlled, and absorbed at the athlete's shoulder. When momentum from the proximal body segments is not transferred to the distal segments effectively, more torque must be developed by the shoulder musculature (Seroyer et al., 2010; Stodden, Fleisig, McLean, & Andrews, 2005; Young et al., 1996). Shoulder joint torque is comprised of shoulder joint forces and moment arms, and great shoulder joint forces are the likely cause of non-contact, throwing injuries. An anterior and superior shoulder joint shear force of about 400 N is generated during the arm acceleration phase of the overarm throwing motion, as the throwing arm moves towards the throwing direction (Feltner & Dapena, 1986; Fleisig, Andrews, Dillman, & Escamilla, 1995; Ouellette et al., 2008). A compressive shoulder joint force of about 1000 N is generated during the arm deceleration phase of the overarm throwing motion (Feltner & Dapena, 1986; Fleisig et al., 1995; Ouellette et al., 2008). The joint forces generated each time an athlete throws a ball, occurring thousands of times per year, have been proposed as risk factors for the relatively common rotator cuff and glenoid labrum injuries sustained by overarm throwing athletes (Fleisig et al., 1995). Investigating how angular momentum is transferred from the lower trunk to the shoulder can provide practical information about the joint forces that have been proposed as non-contact overarm throwing injury risk factors.

To better understand how overarm throwing athletes can optimize ball velocity while minimizing injury risk, the purpose of this thesis was to explore the relationship between the maximum angular momentum of the lower trunk and the throwing shoulder joint resultant compressive and shear forces during the overarm throwing motion of baseball athletes.

## Research Hypotheses

H1: I hypothesized that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint anterior shear force at ball release of the baseball overarm throwing motion.

H2: I hypothesized that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint compressive force at ball release of the baseball overarm throwing motion.

## Delimitations

The delimitations of this study are:

1. Subjects were healthy (no injuries in past 12 months), played baseball at the high school, college, or professional level, and had ages ranging from 18-30 years.
2. Use of the study questionnaire to determine demographic information, injury history, and other sport specific information.
3. Subjects threw for distance and accuracy in simulated game situations from 36.6 meters (120 feet) on an outdoor or indoor baseball practice facility.
4. Vicon Motus software was used to calculate three-dimensional body landmark coordinates.
5. MotionSoft and MatLab software was used to calculate body kinetics and kinematics.

6. Vicon Motus was used to calculate ball velocity after being verified with a Bushnell radar gun.

## Limitations

The limitations of this study include:

1. Some of the subjects played on the same team and had the same coaches, while others did not.
2. Subjects had varying levels of skill.
3. Subjects were assumed to have answered the study questionnaire honestly.
4. Subjects were assumed to have given full effort when throwing and tried to be accurate with their throw.
5. Research throwing may not replicate the same amount of stress as a game.
6. Subjects may have had varied amounts of days not throwing before testing.
7. Training regimen was not controlled, and no training intervention was provided to the subjects.

## Key Terms & Operational Definitions

Arm acceleration phase: This phase describes the period after shoulder maximum external rotation, when the throwing arm begins to rapidly accelerate and rotate forward, ending at ball release (overarm throwing motion) (Dillman, Fleisig, & Andrews, 1993).

Arm cocking phase: In this phase the athlete rotates their throwing arm backwards and reaches maximum external rotation of the shoulder; the phase ends once the throwing arm begins to move forward (overarm throwing motion) (Dillman et al., 1993).

Arm deceleration phase: The period after ball release when the body works to slow itself down during the overarm throwing motion (Dillman et al., 1993).

Ball release: The moment the ball leaves the players hand, and the player can no longer apply force to the ball (Zheng et al., 2004).

Foot contact: The instant the lead foot contacts the ground when a player is throwing the ball (Fleisig, Diffendaffer, & Slowik, 2017).

Infielder: A baseball or softball player that plays a position in the infield. These positions include a catcher, first-baseman, second-baseman, shortstop, and third-baseman.

Inverse dynamics: Use of Newton's second and third laws to calculate net force at each joint of a linked rigid segment system.

Joint angle: The three-dimensional Euler angle between two body segments in a local reference frame with a z, y, x rotation order.

Kinetic chain: A proximal-to-distal sequence in which momentum is transferred from body segment to body segment creating the greatest amount of force at the distal end of the chain (Feltner & Dapena, 1989; Putnam, 1993).

Lead foot: the lead foot is the front foot of the player that is throwing. If the player is right-handed it is their left foot; if the player is left-handed, it is their right foot; also known as contact foot (Fleisig et al., 2017).

Outfielder: Refers to a baseball or softball player that plays in the outfield. These positions include the right fielder, the left fielder, and the center fielder.

Lower trunk (pelvis) angular momentum: The product of the angular velocity of the pelvis about a superior-inferior axis and the moment of inertia of the pelvis about a superior-inferior axis.

Proximal-to-distal sequence: Refers to the way (sequence) the body transfers force. In throwing it starts with the more proximal body segments like the legs, hip, and trunk. These proximal segments generate force and then transfer the force to the distal segments like the wrist and hand, which causes an efficient movement and the greatest amount of force to occur at the hand (distal) (Feltner & Dapena, 1989; Putnam, 1993).

Push-off foot: The back foot of the athlete that uses the ground to push off in the very beginning of the throwing motion to generate an anterior movement; if the player is right-handed it is the right foot; if the player is left-handed it is the left foot (MacWilliams et al., 1998).

Shoulder joint resultant compressive force: The net shoulder joint force that is directed perpendicular to the shoulder joint surface as defined by the upper trunk reference frame.

Shoulder joint resultant shear force: The net shoulder joint force that is directed parallel to the shoulder joint surface as defined by the upper trunk reference frame.

Stride phase: A phase in the overarm throwing motion in which the athlete steps forward with their lead foot and begins to rotate their throwing arm up and back (Dillman et al., 1993).

## CHAPTER 2

## LITERATURE REVIEW

### Throwing Phases and Performance

Consistency exists for the throwing phases in both softball and baseball. The six phases of throwing include the wind-up phase, the stride phase, the arm cocking phase, the arm acceleration phase, the arm deceleration phase, and the follow-through phase (Fleisig et al., 1996; Zheng et al., 2004; Rojas et al., 2009). The throwing phases were originally developed and applied to pitching. Based off the previous pitching models, a modified model can be used for non-pitching overarm throwing which includes (A) the stride phase, (B) the arm cocking phase, (C) the arm acceleration phase, and the (D) arm deceleration phase (Figure 1).

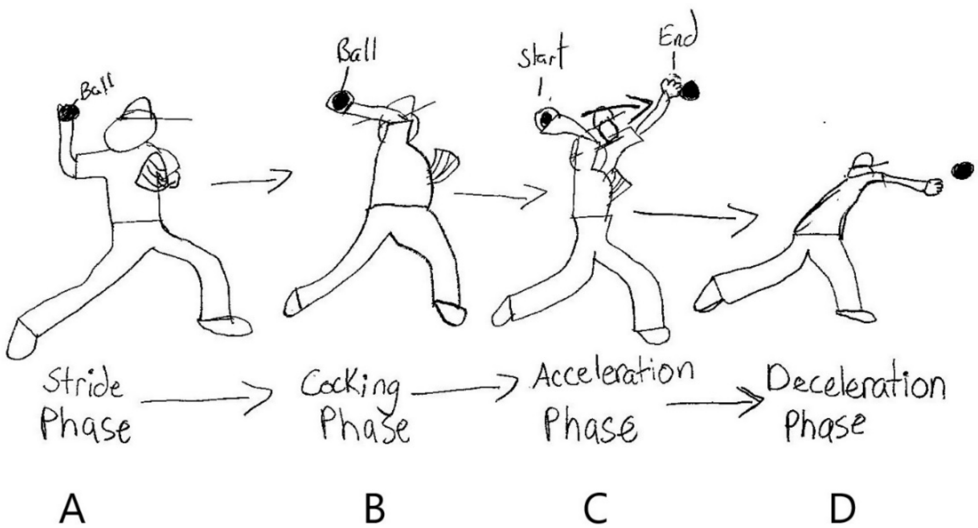


**Figure 1. Throwing Phases**
The modified phases of non-pitching overarm throwing: (A) the stride phase, (B) the arm cocking phase, (C) the arm acceleration phase, and the (D) arm deceleration phase.

Throwing performance is vital to all baseball athletes as it is an important skill for the infielder, outfielder, and the pitcher to use in order to record outs in the game. Research for overarm throwing performance in baseball has focused on pitching. Understanding the different movements in each phase of the overarm throwing motion provides insight on performance. During the stride phase of overarm throwing the following information was presented for improved performance, the lower trunk (pelvis) should begin to face the target while the upper trunk stays closed (positioned slightly to the right for a right-handed pitcher), the throwing shoulder is abducted about 90°, it is horizontally abducted about 20°, it is externally rotated about 50°, and the throwing elbow should be flexed about 90° (Fleisig et al., 2016; Fleisig et al., 2017; Zheng et al., 2004). A higher ground reaction force at the push-off foot and the lead foot during the stride phase is associated with an increase in wrsit and ball velocity (Alexander, 1991; MacWilliams et al., 1998; Young et al., 1996). Maximum trunk axial rotation (approximately 55°) and maximum trunk angular acceleration (approximately 11,600°/$s^2$) also occurred around foot contact in the stride phase (Fleisig, Hsu, Fortenbaugh, Cordover, & Press, 2013). For the stride phase low breaking forces at the lead leg and a short stride compared to the pitcher's height were associated with a decrease in ball velocity (Fortenbaugh, Fleisig, & Andrews, 2009).

During the arm cocking phase, maximum angular velocity of the lower trunk and maximum angular velocity of the upper trunk are related to performance, and in high-level pitchers (college and professional) maximum angular velocity of the lower trunk is around 575°/s and maximum angular velocity of the upper trunk is around 1100°/s (Fleisig et al., 2016; Fleisig et al., 2017). A higher average lower trunk (pelvis) velocity and an average higher upper torso velocity resulted in a higher ball velocity during the arm cocking phase, as well; an increase in lower trunk orientation and upper trunk orientation at the instant of maximum external rotation of the shoulder also resulted in increased ball velocity (Stodden et al., 2005).

During the arm acceleration phase, several joint mechanics have been associated with improved performance. Increased lead knee flexion resulting in  knee extension at the end of the acceleration phase (ball release), increased trunk forward tilt, and increased maximum shoulder angular velocity are all associated with increased ball velocity during the arm acceleration phase (ball release) (Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001; Werner, Suri, Guido, Meister, & Jones, 2008). Increased maximum external rotation and increased elbow extension velocities are also associated with an increased ball velocity (Werner et al., 2008). Research on 18 elite baseball pitchers found that increased lower trunk orientation at maximum external rotation of the throwing shoulder, increased upper trunk orientation at maximum external rotation of the throwing shoulder, increased lower trunk orientation at ball release, and increased upper trunk velocity during arm acceleration were associated with an increased ball velocity (Stodden, Fleisig, McLean, Lyman, & Andrews, 2001).

One of the flaws in the literature related to baseball overarm throwing performance was that it focused on baseball pitching and not position player throwing.

**Kinetic Chain**

The kinetic chain and proximal-to-distal sequence that occurs during complex multi-joints movements such as overarm throwing connects movements of the lower trunk and shoulder. The term kinetic chain refers to how the body transfers energy from one joint to the next (Feltner & Dapena, 1989; Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002; Hirashima et al., 2008; Putnam, 1993; Seroyer et al., 2010). During the kinetic chain sequence in overarm throwing the body develops energy or force in the larger proximal segments (or lower body), and transfers that force to the distal segments of the body (Feltner & Dapena, 1989; Putnam, 1993). When applying the kinetic chain and proximal-to-distal sequence to throwing, the literature did have research on this topic; however, the research again focused on baseball pitching. During the baseball pitching motion, the extreme external rotation of the upper arm mainly occurred due to sequential actions of muscles at the shoulder, but rapid elbow extension at ball release was mainly due to the movement of the upper arm and trunk (Feltner, 1989). Researchers investigating baseball pitching indicated the acceleration of the elbow and wrist were dependent on torque (energy) originally produced by the proximal trunk and shoulder (Hirashima et al., 2008). The main purposes of the previously mentioned studies were focused on developing a method to calculate the energy transferred and the results were more a secondary part of the literature. When non-pitching athletes used a brace to limit certain motions, most of the energy generated during throwing was produced by the lower trunk, and the resulting energy was used to load the elastic properties in the shoulder and transfer the energy to the ball or create the rapid acceleration of the ball (Roach & Lieberman, 2014). Roach and Lieberman (2014) also claimed that the rapid accelerations of the distal segments (wrist and elbow) were generated by the power produced by the proximal segments such as the shoulder and trunk. In college softball position players, the gluteal muscle group played a key role in stabilizing the lower trunk during throwing and helped to transfer energy up the kinetic chain, and trunk flexion and rotation had a positive relationship with shoulder moments which indicated that the actions of the lower trunk and upper trunk are strongly related to throwing performance, especially at the shoulder (Oliver, 2014).

The shoulder and upper arm alone are not able to produce the force that is needed to throw a baseball at a high velocity (Fleisig et al., 1995; Pappas, Zawacki, & Sullivan, 1985; Roach & Lieberman, 2014). Since the shoulder and upper arm cannot produce enough force on their own, the kinetic chain sequence (proximal-to-distal) is essential for efficient force transmission during the throwing motion as the force must be produced and transferred from other body segments. The process begins with the push-off foot. The push-off foot generates force by reacting with the ground, and this force is then transferred anteriorly to the lead foot

(MacWilliams et al., 1998; Young et al., 1996). The lead foot and lead leg accept the force, and generate more force which is sent up to the lower trunk (Fortenbaugh et al., 2009; MacWilliams et al., 1998). In both baseball and handball the more experienced and efficient athletes are able to better utilize and transfer ground reaction force which results in more force being applied to the ball (increased velocity) (MacWilliams et al., 1998; Rousanoglou, Noutsos, Bayios, & Boudolos, 2014). Once the force is transmitted to the lower trunk it becomes angular as the lower trunk rotates (Young et al., 1996). The lower trunk and upper trunk are responsible for generating a large sum of the forces, taking the load off of the shoulder musculature (Burkhart, Morgan, & Kibler, 2003). While the generation of the force by the trunk is essential, the timing of the sequence is as important. Professional pitchers do not exhibit a large difference in lower trunk torque, but they exhibit a difference in the timing of the lower trunk rotation (efficient transfer of force) (Stodden et al., 2001). In less experienced and less efficient baseball players the shoulder musculature is more active, while in professional pitchers the activation of the shoulder musculature is more selective and less active as they utilize the proper timing of the larger muscles of the lower trunk and upper trunk to generate and transfer force (Gowan, Jobe, Tibone, Perry, & Moynes, 1987; Young et al., 1996). If there is a small reduction in force form the pelvis and trunk, it would require a large increase in force produced by the shoulder to generate the same amount of force on the ball (Seroyer et al., 2010). The upper trunk generates and receives rotational force from the lower trunk, generates force by leaning forward, works to absorb some of the force towards the end of the throwing motion, and has an important role in maintaining stiffness in the muscles which transfers force by releasing elastic stored energy to the shoulder (McGill & Hoodless, 1990; Oliver, 2014; Santana, McGill, & Brown, 2015; Stodden et al., 2005; Young et al., 1996). The muscles of the trunk are connected to the scapula, and the scapula is essential in transferring the forces from the lower trunk and upper trunk, to the distal shoulder, elbow, and hand (Kibler, 1998). The shoulder receives the forces transferred from the rest of the body segments and internally rotates, which generates and transfers the forces to the rest of the distal segments (Hirashima et al., 2008; Roach & Lieberman, 2014). Finally the force is applied from the hand to the ball, causing the ball to move. During this process, the transfer of force during throwing motion, the body segment begins to move as the adjacent proximal segment reaches maximum velocity, as this allows for the greatest accumulation of force at the most distal body segment, resulting in the greatest amount of force being applied to the ball (Putnam, 1993).

The serape effect is a phenomenon that occurs during the throwing motion which results in an increased efficiency of force transmission through the kinetic chain (Santana, 2003; Santana et al., 2015). The serape effect refers to an eccentric contraction or stretching of the diagonal muscle groups which causes an elastic storage, and when the elastic storage is released it allows for an increased force production in rotational movements (Collins, Adamczyk, & Kuo, 2009; Kaur et al., 2014; Konin, Beil, & Werner, 2003; Logan & McKinney, 1970; Santana, 2003; Santana et al., 2015). In the stride phase of the right handed athlete, the left portion of the upper body moves to the right, back, and down, while the pelvis moves forward and to the left creating an elastic storage of the posterior serape (diagonal muscles of posterior stretch) (Santana et al., 2015). The posterior serape is then released generating force production and it elicits the anterior serape to become stretched as the left portion of the upper body then moves forward and to the left, while the right portion of the upper body moves back and towards the right (Santana et al., 2015). The anterior serape elastic storage is then released, which generates high amounts of rotational force at the hips and trunk, which allows for more force to be applied to the ball while reducing the work of the shoulder muscles as the release of the elastic storage is a passive movement, not an active concentric contraction (Collins et al., 2009; Kaur et al., 2014; Konin et al., 2003; Logan & McKinney, 1970; Santana, 2003; Santana et al., 2015).

**Inverse Dynamics**

To properly study the throwing motion, understanding the existing methods in the literature and which method best applies to the desired research topic is vital. Several methods are available for studying the overarm throwing motion. The first method is the *inverse dynamics model*. Inverse dynamics takes kinematic and inertial data and calculates the forces or moments at limb segments, and using link-segment models Newton's Laws of Motion representing the mechanical behavior of limb motion allows researchers to determine net forces and moments at each joint (Bisseling & Hof, 2006; Otten, 2003). For example, the mass of the ball is known, and the acceleration of the ball will be calculated. When the mass of the ball is multiplied by the acceleration of the ball, the force being applied to the ball is determined (Force = mass * acceleration) (Otten, 2003). Once the force is determined, the force opposite and equal from the ball to the knuckle can be calculated (Newton's third law). Using these principles you can get the net forces at each joint (Bisseling & Hof, 2006; Otten, 2003). It is possible to determine the mass of a limb segment needed for the inverse dynamics technique from the subject's total mass, as researchers have determined percentages for each limb segment (de Leva, 1996). Another method used in research to calculate the net joint forces is the *forward dynamics model*. In this model, the researcher knows the internal forces and torques, thus the resulting forces of the movement in question, and then the known forces are used to determine how the person should move; this model has been used in the study of gait (Zajac, Neptune, & Kautz, 2002). The inverse dynamics model has been used in previous throwing research and is acceptable (Stodden et al., 2005). Due to the fact that the inverse dynamics model actually calculates the net force or moment at the joint, it appears to be better for baseball throwing.

Feltner and Dapena (1989) first developed a general model using the net forces from the inverse dynamics model to determine how the energy was transferred from each joint (Feltner & Dapena, 1989). More recently in 2008, a 3D model called induced acceleration analysis was created and successfully applied to baseball pitching (Hirashima et al., 2008). In the induced acceleration analysis, the net forces developed from the inverse dynamics model are used to determine the amount of force developed by the joint, along with the amount of force transferred from previous body segments (Hirashima et al., 2008).

When examining the available research techniques, it appears that the inverse dynamics model will be the best for the purpose of this research. The inverse dynamics model is more appropriate than the forward dynamics model for this study because of the need to calculate the force and the movements of the subjects during the throwing motion. The inverse dynamics model will allow me to determine the relationship between the lower trunk and the shoulder during throwing, which will allow me to properly test the two hypotheses for this study. Calculating forces via inverse dynamics are better than estimating them, as is done in the forward dynamics model (more appropriate for simulating movements).

The overarm throwing motion utilizes the kinetic chain sequence to transfer momentum and develop force. The athlete's performance depends heavily on the efficient transfer of momentum from the proximal body segments to the distal body segments to apply force on the ball. There is a direct relationship between the change in angular momentum of the proximal body segment and the rotational force (torque) of the corresponding distal joint. Rapid elbow extension and ball velocity at release is due to the preceding movements of the upper arm and trunk segments (Feltner, 1989). Therefore the purpose of this study is to explore the relationship between the angular momentum of the lower trunk and the throwing shoulder joint resultant and shear forces during the overarm throwing motion in baseball using kinetics, kinematics, and inverse dynamics.

## Injuries

### General Population Prevalence

In the general population mixed information exists when reviewing shoulder injury prevalence and incidence literature. In the UK the prevalence of upper arm pain for at least one day, which included shoulder and elbow pain, was 52% (Walker-Bone, Palmer, Reading, Coggon, & Cooper, 2004). Shoulder pain prevalence in the general population for adults younger than 70 years old ranged from 5-47% of the population (Kuijpers, van der Windt, van der Heijden, & Bouter, 2004; Luime et al., 2004). When broken down a one month prevalence of shoulder pain in 9-31% of the population was found, and a one year prevalence in 5-47% of the population was found (Luime et al., 2004). A 52% prevalence of upper arm pain, with 34.4% being shoulder pain was reported in the UK (Walker-Bone et al., 2004). In the Netherlands there is approximately a point prevalence of 21% for shoulder pain (Picavet & Schouten, 2003). In Sweden a prevalence of 23% for shoulder pain was reported and in the UK a prevalence of 34% was reported (Brattberg, Thorslund, & Wikman, 1989; Pope, Croft, Pritchard, & Silman, 1997). A prevalence of 20.7% was reported for rotator cuff tears in Japan (Yamamoto et al., 2010). It was also interesting to note that individuals with repetitive jobs seemed to have a higher shoulder pain prevalence. About 29% of people who participated in repetitive work had shoulder pain, compared to 16% of people who did not participate in repetitive work (Leclerc et al., 2004).

The large ranges in shoulder pain reported in the review, and the differences in the prevalence rates from the articles, are mainly due to three reasons. First, the studies had varying definitions of shoulder pain (Luime et al., 2004; Pope et al., 1997; Walker-Bone et al., 2004). Second, the age of the population observed in the studies also affected the prevalence rates as the older population had higher prevalence rates (Kuijpers et al., 2004; Luime et al., 2004). The country or area where the subjects lived may have influenced prevalence rates due to different lifestyles within those countries (Brattberg et al., 1989; Luime et al., 2004; Pope et al., 1997; Yamamoto et al., 2010). While there was a large variation in reported prevalence for the shoulder, it was clear through the literature that people were affected by shoulder pain.

**Overarm Throwing Prevalence**

Overarm throwing sports require high force and fast movements of the shoulder, which put these athletes at risk for an injury. Seventy-five percent of high-level track and field throwers presented one or more injuries of the throwing arm during their career (Edouard, Depiesse, & Serra, 2010). Of the 75% of track and field athletes that sustained a throwing injury, the shoulder was injured most frequently (70%) (Edouard et al., 2010). In the MLB, the shoulder and elbow are the two most common body parts injured, accounting for 40.2% of all injuries (shoulder 20.6%; elbow 19.6%) (Conte et al., 2016). The prevalence of a Bennett lesion of the shoulder in MLB pitchers was 22% (Wright & Paletta, 2004). During high school softball practice, 68.2% of the shoulder injuries occurred from overarm throwing (not including pitching) and during baseball practice 41.9% of the shoulder injuries occurred from pitching (Krajnik et al., 2010). Noncontact or overuse injuries accounted for 67% of injuries in baseball, and 78% of injuries in softball which is important because injuries caused by the overarm throwing motion are considered noncontact (Krajnik et al., 2010). The shoulder injury rate in baseball was 1.72

injuries per 10,000 athlete exposures, and for softball, it was 1.00 injuries per 10,000 athlete exposures (Krajnik et al., 2010). One of the issues with the available baseball and softball literature is the fact that most of the literature looking at shoulder pain prevalence related to throwing, focuses on pitching in both softball and baseball (Conte et al., 2015; Shanley, Michener, Ellenbecker, & Rauh, 2012). The focus of this study is on non-pitching overarm throwing.

### General Population Cost

In 1994, a group of researchers in the United States investigated four common shoulder procedures (primary open rotator cuff repair, anterior instability repair, arthroscopic subacromial decompression, and total shoulder arthroplasty) to evaluate the cost to consumers finding that on average, only 36% of the participants had workers compensation, and it cost $10,422 per person (range from $7,246-$16,323) (Milne & Gartsman, 1994). In Sweden during 2012, the average healthcare cost for shoulder pain was $389 per person during a six month period, and the average annual cost was $4,791 per person (Virta, Joranger, Brox, & Eriksson, 2012). Research has also indicated that neck and shoulder pain is credited with accounting for 18% of insurance disability payments (Nygren, Berglund, & von Koch, 1995).

### Overarm Throwing Cost

Injuries cost the MLB $423,267,634 per year, and a total of $7,618,817,407 over the span of 18 years (Conte et al., 2016). There is very limited literature on the cost in money. It makes sense that the cost was applied to MLB as the league generates a lot of revenue and the players earn money, which makes evaluating the cost easier.

Another type of cost, days lost and return to play, was covered in more detail. Starting with throwing sports in general, 75% of high-level track and field throwers suffered an injury, and 40% of the injured throwers lost over 28 days due to the injury (Edouard et al., 2010). In high-level college softball pitchers 11 out of 26 injuries resulted in lost playing time, and 82% of those injuries occurred in the upper body (Loosli, Requa, Garrick, & Hanley, 1992). In high school baseball 42% of the shoulder injuries resulted in 7 to 21 lost playing days (Krajnik et al., 2010). Twenty-seven professional baseball players underwent shoulder surgery, and 15 of those players either retired after shoulder surgery, or never made it back to the same-level of play (Cohen, Sheridan, & Ciccotti, 2010). After slap tears (superior labral tear of the shoulder) 61% of the baseball players who did not undergo surgery never returned to play, and 15% of the baseball players who did undergo surgery never returned to play (Fedoriw, Ramkumar, McCulloch, & Lintner, 2014). Fourteen professional baseball players (12 pitchers, one shortstop, and one outfielder) underwent surgery to repair a full-thickness rotator cuff tear, and six of the 14 players (five pitchers and one shortstop) (43%) never returned to play (Mazoue & Andrews, 2006).

**Injury Mechanisms**

Shear and compressive forces during the overarm throwing motion are linked to shoulder injuries. The overarm throwing motion in baseball generates a high anterior shear force of about 400 Newtons (N) and a high compressive force of about 650 N during the late arm cocking and early arm acceleration phases of throwing (Feltner & Dapena, 1986; Fleisig et al., 1995; Meister, 2000; Ouellette et al., 2008). The anterior and superior shear forces and the compressive forces during the late arm cocking and early arm acceleration phases were proven to be linked to glenoid labral tears and biceps tendon injuries (Braun et al., 2010; Fleisig et al., 1995; Ouellette et al., 2008; Snyder, Karzel, Del Pizzo, Ferkel, & Friedman, 1990). During the deceleration phase of the overarm throwing motion in baseball a high posterior shear force of about 400 N, high inferior shear force, and high compressive force of about 1000 N is generated (Feltner & Dapena, 1986; Fleisig et al., 1995; Meister, 2000; Ouellette et al., 2008). The shear forces and compressive forces during the deceleration phase are connected to rotator cuff injuries, labral tears of the shoulder, and bicep tendon injuries (Braun et al., 2010; Fleisig et al., 1995; Ouellette et al., 2008; Snyder et al., 1990). While the literature focused on baseball pitching, it was clear that the high shear and compressive forces during the overarm throwing motion were associated with shoulder injuries.

The high shear and compressive forces that are correlated with injuries to the shoulder during the overarm throwing motion are multifaceted, and due to the complex interaction between different body segments during the overarm throw, the injuries that occur at the shoulder can be caused by improper mechanics at other parts of the body. Improper timing of trunk rotation causes an inefficient force transfer from the trunk to the shoulder which was associated with a higher proximal force at the shoulder, and a higher internal rotation torque at the shoulder (Oyama et al., 2014). Fatigue of the lumbar spine musculature is associated with potential for compensatory muscular injury, and fatigue of the lumbar spine musculature reduces the elastic storage properties of the muscle (serape effect), which is associated with an increased stress on the shoulder (Watkins et al., 1989; Young et al., 1996). An alteration in the shape of the thoracic spine can cause the scapula to change its position, which can reduce clearance of the humeral head and increase the shear force on the shoulder (Fu, Harner, & Klein, 1991; Hertling, Kessler, & Shimandle, 1990; Kibler, 1998; Young et al., 1996). The complex interaction between body segments and injury risk make understanding the relationship between the lower trunk and the forces at the shoulder crucial to improving injury prevention.

The kinetic chain sequence used during the overarm throwing motion in baseball identifies how important the transfer of momentum form the proximal body segments to the distal body segments are to the athlete's success and risk of injury. Using the inverse dynamics model we can determine how the transfer of momentum from the lower trunk affects the shear and compressive forces applied to the shoulder. Understanding the relationship between the lower trunk and the shoulder during the overarm throw yields the potential to create a more efficient transfer of momentum, and reduce the amount of forces applied to the shoulder, which would result in better performance and reduce the risk for an injury. To better understand how overarm throwing athletes can optimize ball velocity (performance) while minimizing injury risk, the purpose of this thesis is to explore the relationship between the maximum angular momentum of the lower trunk and the throwing shoulder joint resultant compressive and shear forces during the overarm throwing motion of baseball athletes.

# CHAPTER 3

## METHODS

### Experimental Approach to the Problem

The purpose of this thesis was to explore the relationship between the angular momentum of the lower trunk and the throwing shoulder joint resultant compressive and shear forces during the overarm throwing motion. I hypothesized that there would be a negative correlation between the maximum angular momentum about the superior and inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint anterior shear force at ball release of the overarm throwing motion. I also hypothesized that there would be a negative correlation between the maximum angular momentum about the superior and inferior axis of the lower trunk during the arm cocking phase and the maximum throwing shoulder joint compressive force at ball release of the overarm throwing motion. The independent variable was: the angular momentum of the lower trunk (pelvis). The lower trunk was defined in width from the right hip to the left hip, and defined in length from the midpoint of the right and left hip to the sacrum. The dependent variables were: shear force at the shoulder joint and compressive force at the shoulder joint. The covariates included age, years played, dominant arm, position (infield, outfield, and pitcher), release speed (ball velocity), height, and weight. The study was a cross-sectional observational design.

### Subjects

A total of 24 male subjects who currently play or played baseball competitively were tested. The subjects were 22.8 ± 3.6 years of age, had a height of 1.83 ± 0.07 meters, weighed 90.3 ± 13.9 kg, had a release speed (ball velocity) of 31.6 ± 3.9 m/s, and had 14.5 ± 4.2 years of playing experience. Two of the subjects were left-handed, and the remaining 22 were right-handed. Fourteen of the subjects were pitchers, seven infielders (two second baseman, one shortstop, two third baseman, and two first baseman), and three outfielders. Fifteen of the subjects' highest level of play was college baseball (twelve played at the D1 level, and three played at the D3 level), three of the subjects' highest level of play was professional baseball, and six of the subjects' highest level of play was at the high school level. The inclusion criteria were: overarm throwers, subjects that played or currently play baseball at the high school, college, or professional level, subjects who played a position that was required to throw during the sport (infielder, outfielder, and pitcher), subjects who had at least three years of throwing experience in a competitive situation, subjects who were 18 years of age or older, and subjects who had been healthy for at least one year before being tested. Healthy was categorized as no hip, trunk, shoulder, or elbow surgeries in the past year or any current injuries. The subjects were healthy and had experience throwing in a game to prevent variance from causing an error in the data collected. The exclusion criteria included: underarm or sidearm throwers, subjects who did not play competitive baseball at the high school, college, or professional level, subjects who did not have three years of throwing experience in a competitive situation, designated hitters, and subjects who were not considered healthy at the time of testing. Subjects filled out an informed consent and injury/information questionnaire that was approved by the local IRB before being tested. All aspects of the study, including ethics and safety, were approved by the local IRB (IRBNet ID 1314003-1 provided in appendix A).

**Protocol**

Testing was conducted at three different practice facilities. Seven of the subjects were tested outdoors on a grass baseball field located in Huntington, West Virginia. Six of the subjects were tested at an indoor practice facility in Portsmouth, Ohio. Eleven of the subjects were tested at an outdoor grass baseball field in Wayne, New Jersey. The researcher explained the entire procedure and answered any questions the subject had. The subject was instructed to wear a tight-fitting shirt, and tight-fitting shorts to increase the accuracy of the data collected when using the Vicon Motus (Vicon, Oxford, UK) manual digitizing software. The athlete was also instructed to wear cleats or athletic shoes (indoor facility) to replicate a game situation. The subject was not required to wear a hat and or sunglasses but was allowed to if he wanted to. The subject brought their baseball glove with them.

The subject was then allowed to warm-up before the testing. The subject was instructed to warm-up as they would before a game, and no time limit was placed on the warm-up. The subject also threw the ball back and forth with one of the researchers until they felt ready to throw the ball at maximum velocity. The subject threw a regulation NCAA baseball weighing 0.142 kg.

Four cones were used to mark the throwing area which was approximately 3 meters long and 2 meters wide. The throwing area was in the middle of the outfield for the outdoor locations, and for the indoor location, the throwing area was in the back corner of the practice facility. A Rukket Sports seven by seven foot throwing net (Rukket Sports, Wilmington, DE) was placed exactly 36.58 meters (120 feet) from the middle of the throwing area. At the outdoor locations, the Rukket Sports net was placed in the infield directly behind second base (36.58 meters away from the throwing area). At the indoor practice facility, the Rukket Sports net was placed in the corner opposite of the throwing area (36.58 meters away from the throwing area). The subject was instructed to throw the ball with at least 90% effort at the Rukket Sports net placed 36.58 meters away, and directly in front of them. The subject was handed a baseball and told to throw the ball at the net as if they were trying to throw out a base runner. The subject was allowed but not required to take one step before throwing (whichever was more natural), and the subject was allowed to practice throwing at the net to become comfortable before testing. For the trial to be considered successful, the subject had to start and end their throwing motion within the throwing area marked by the cones, and the subject had to hit the Rukket Sports net. Each subject completed three successful throwing trials.

**Instrumentation**

A radar gun (Bushnell, Overland Park, KS) with a manufacturer stated variance of +/- 1 mph was used to measure the subject's throwing velocity. A Rukket Sports seven by seven foot throwing net (Rukket Sports, Wilmington, DE) was used as the throwing target. Two Sony RX10 III video cameras (Sony, Tokyo, Japan) capturing at 59.94 frames per second (fps) were used to record the subject. Four custom made poles with nine points on them spaced 0.305 meters apart were used for calibration. Contemplas Templo software (Contemplas, Kempten, Germany) was used to trim the 2D video recordings obtained from the cameras. Vicon Motus software (Vicon, Oxford, UK) was used to digitize anatomical landmarks on the subject from the 2D video recordings. The 2D coordinates, obtained from the digitizing, were converted to 3D coordinates, and position data was established using custom-built MotionSoft software (MotionSoft LLC., Durham, NC, USA). MotionSoft and a custom built MatLab (Mathworks Inc., Natick, MA) program were used to calculate kinematic and kinetic data. SPSS version 22 (IBM, Chicago, IL) was used for statistical analysis. G*Power software (Heinrich Heine University Düsseldorf, Düsseldorf, Northrhine-Westphalia, Germany) was used to determine the sample size needed.

**Data Collection**

An appropriate location in the outfield or the indoor facility was chosen to be the capture volume where forward (positive X) was the throwing direction. Two high-speed cameras (Sony, Tokyo, Japan) capturing at 59.94 fps were used to record every throw. One camera was placed on the right side of the capture volume, and one camera was placed behind the capture volume (Figure 2). The angle between the optical axes of the two high-speed cameras was approximately 90° (Figure 2). A calibration frame was used at the indoor complex and outdoor baseball fields to calibrate the high-speed cameras' positions and orientations in reference to the capture volume. The calibration frame consisted of four poles with nine points on each pole, with a total of 36 points (Figure 2). Each point on the pole was a known 0.305 meters apart. Thirty-six control points were selected because it is more than the minimum number of 16 points which are required for acceptable accuracy (Chen, Armstrong, & Raftopoulos, 1994). A rectangle was formed with the poles around the capture volume. The volume of the rectangle was approximately 2.00 meters for the width, 3.00 meters for the length, and 2.75 meters for the height (Figure 2). The distance between all the poles was measured using a steel measuring tape. Five markers (cones) were placed on the ground in the middle of the capture volume to establish a global reference frame for the data reduction process (Figure 3). For the global reference frame the positive X was forward (the throwing direction), the positive Y was to the left, and the positive Z was up. One researcher also stood directly behind the subject with a radar gun (Bushnell, Overland Park, KS) and they measured the ball velocity at the subject's hand for the first three subjects to validate using Vicon Motus for release speed (ball velocity).

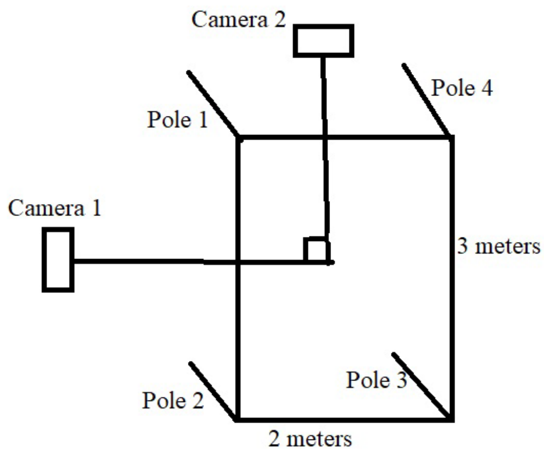


**Figure 2. Data Collection Setup**
A top-down view of the setup of the four calibration poles and camera positioning for calibration. The black lines by the camera represent the line of the optical axes of the camera, which meet at a 90° angle. Each pole had nine calibration points on it spaced 0.305 meters apart vertically.

### Data Reduction

The best trial out of the three recorded for each subject was selected for data processing. The best trial was based on the accuracy of the throw, and accuracy was determined qualitatively by the ball hitting the center of the Rukket Sports net. One trial was re-digitized and processed for one subject at each location to assess measurement error. All three recorded trials were digitized and processed for two subjects at each location to assess the consistency of movement kinematics within subjects. The calibration video clips and the selected throwing video clips were exported from the cameras and then trimmed in the Contemplas Templo software (Contemplas, Kempten, Germany). For the calibration videos, two frames with no movement or obstructions of view were trimmed. For the throwing trials, the start of the video was when the subject's lead foot came off the ground, and the end of the video was five frames after the ball left the subject's hand (5 frames after ball release).

## Data Processing

Once the videos were trimmed, they were uploaded into the Vicon Motus manual digitizing software (Vicon, Oxford, UK). The nine points on all four poles were digitized in order, starting with the bottom point of pole 1 moving up until all 9 points on the pole were selected. Then pole 2, pole 3, and pole 4 were digitized in the same manner. The trimmed video from both the side and back view of the athlete was also digitized using Vicon Motus. Twenty-three anatomical landmarks on the subject were digitized for each trial and view. The twenty three landmarks included the top of the head (vertex), the chin, the suprasternal notch, the right shoulder, the left shoulder, the right elbow, the left elbow, the right wrist, the left wrist, the right middle knuckle, the left middle knuckle, the right hip, the left hip, the sacrum, the right knee, the left knee, the right ankle, the left ankle, the right heel, the left heel, the right middle toe, the left middle toe, and the ball (baseball). For any landmark that was obstructed in a frame, the best estimate of the location of the landmark was digitized.

The 2D coordinates were then mathematically synchronized. Three critical instants of throwing were identified. Foot contact, maximum external rotation, and ball release were identified from each high-speed camera view for every trial. The identification process was done qualitatively by watching the recorded video.

An XYZ global reference frame was created using the top points of the five cones which came from the same calibration video with the four poles (Figure 3). Cone one was placed in the middle of all the cones, and defined the origin. Cone two was placed in the throwing direction between cone one and the throwing target. Cone three was placed behind cone one, directly away from the throwing direction. Cone four was placed to the left of cone one. Cone five was placed to the right of cone one. The global X-axis was defined as a straight line joining cones 2, 1, and

3. The positive X-axis direction pointed towards cone 2 and the negative X-axis direction pointed towards cone 3. The global Y-axis was defined as a straight line joining cones 4, 1, and 5. The positive Y-axis direction pointed towards cone 4 and the negative Y-axis direction pointed towards cone 5. The global Z axis was defined as the cross product of the X and Y axes with up as positive.

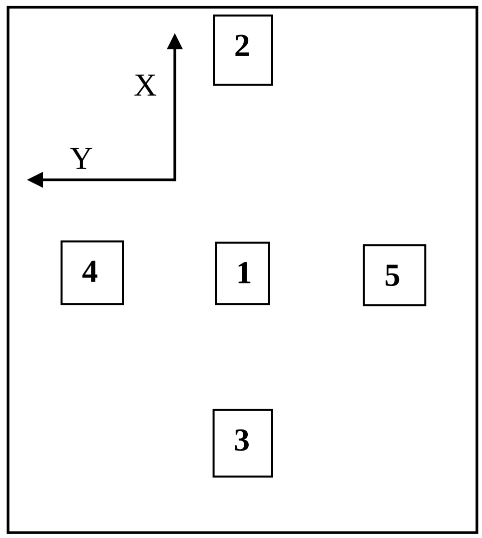


**Figure 3. Five Cones Inside Capture Volume for Global X, Y, Z Axis**
A top-down representation of the configuration of the cones inside the capture volume used to create the X, Y, Z global axes. Cone one is the origin, cone two defines the positive end of the X-axis (toward the throwing target), cone three defines the negative end of the X-axis, cone four is to the left and defines the positive end of the Y-axis, and cone five is to the right and defines the negative end of the Y-axis.

Using the calibration points from the four poles, the Direct Linear Transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to obtain real-life three-dimensional (3D) coordinates of the global reference markers, anatomical body landmarks, and the center of the ball (softball or baseball) from the 2D coordinates. The calibration points were used as inputs to the DLT equations (equation 1 and 2). The conversion factors from the image-plane reference frame as digitized on the horizontal axis of the screen to the object-space reference frame was calculated as:

$$u = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad \text{(Eqn 1)}$$

where: *u* was the horizontal axis of the screen in the image-plane reference frame, $L_n$ refers to the DLT parameters, *X* was the object-space reference frame x-axis, *Y* was the object-space reference frame y-axis, and *Z* was the object-space reference frame z-axis.

The conversion factors from the image-plane reference frame as digitized on the vertical axis of the screen to the object-space reference frame was calculated as:

$$v = \frac{L_5X + L_6Y + L_7Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad \text{(Eqn 2)}$$

where: *v* was the vertical axis of the screen in the image-plane reference frame, $L_n$ refers to the DLT parameters, *X* was the object-space reference frame x-axis, *Y* was the object-space reference frame y-axis, and *Z* was the object-space reference frame z-axis.

The mean error calculated from the calibration points was 9.94 mm. The estimated 3D coordinates were filtered using a Butterworth low-pass digital filter with an optimal cut-off frequency of 7.14Hz (Yu and Andrews, 1998). The synchronization of the digitized 2D coordinates, the direct linear transformation of the digitized 2D coordinates to real-life 3D coordinates, and data smoothing was performed using software which was custom written for the task in visual basic by MotionSoft. The MotionSoft 2016 version was used.

The ball was defined as a point mass at the location of the ball landmark. The hand was defined as a truncated cone between the wrist landmark and the middle knuckle landmark. The forearm was defined as a truncated cone between the elbow landmark and the wrist landmark. The upper arm was defined as a truncated cone between the shoulder landmark and the elbow landmark. The thigh was defined as a truncated cone between the hip landmark and the knee landmark. The lower leg (shank) was defined as a truncated cone between the middle knee landmark and the ankle landmark. The foot was defined as a wedge between the ankle landmark, the heel landmark, and the toe landmark. The head was defined as a sphere between the head landmark (vertex) and the chin landmark. The trunk was defined as a cylinder with width determined by the left and right hips and height determined by the hips and shoulders. The upper trunk was defined as a cylinder with width determined by the left and right shoulders and height determined by the suprasternal notch and shoulders. The lower trunk was defined as a cylinder with a width determined by the left and right hips and height determined by the sacrum and hips.

The local reference frame of the lower trunk was determined by the right hip, left hip, and right knee landmarks so that x was positive anterior, y was positive left, and z was positive upwards. The local reference frame of the upper trunk was determined by the right shoulder, left shoulder, and suprasternal notch landmarks so that x was positive anterior, y was positive left, and z was positive upwards. The local reference frame of the upper arm was determined by the right shoulder, right shoulder, and right wrist landmarks so that x was positive anterior, y was positive left, and z was positive upwards. The local reference frame of the forearm was determined by the right elbow, right wrist, and right knuckle landmarks so that x was positive anterior, y was positive left, and z was positive upwards.

The segment angles were calculated as Euler angles of the segment reference frame with respect to the global reference frame in an x, y, z rotation order. The segment angular velocities and accelerations were calculated as the first and second derivatives of angular position with respect to time, respectively. The segment length of the lower trunk was calculated as the vector pointing from the coordinate of the sacrum marker to the coordinates of the midpoint of a line joining the left and right hip markers, the segment length of the hand was calculated as the vector pointing from the coordinate of the wrist marker to the coordinate of the third knuckle marker, the segment length of the forearm was calculated as the vector pointing from the coordinate of the elbow marker to the coordinate of the wrist marker, and the segment length of the upper arm was calculated as the vector pointing from the coordinate of the shoulder marker to the coordinate of the elbow marker. The COM coordinates were calculated from the landmark coordinates. The COM coordinates for the hand were calculated as 62.8% of the distance from the wrist to the middle knuckle in the x-axis, 51.3% in the y-axis, and 40.1% in the z-axis (de Leva, 1996). The COM coordinates for the forearm were calculated as 27.6% of the distance from the elbow to the wrist in the x-axis, 26.5% in the y-axis, and 12.1% in the z-axis (de Leva, 1996). The COM coordinates for the upper arm were calculated as 28.5% of the distance from the shoulder to the elbow in the x-axis, 26.9% in the y-axis, and 15.8% in the z-axis (de Leva, 1996).

Once the 3D coordinates were calculated and smoothed, landmark coordinates, segment angles, segment angular velocities, segment angular accelerations, segment lengths, segment centers of mass (COM) coordinates, and segment COM accelerations were obtained using the MotionSoft software.

The maximum angular velocity of the lower trunk was selected from the MotionSoft output qualitatively by identifying the frame in which the arm cocking phase started, and finished, and then the maximum lower trunk velocity in between those frames was identified for each subject (radians per second). The lower trunk moment of inertia was calculated by multiplying the mass of the lower trunk by the radius of gyration squared. The mass of the lower trunk (pelvis) was calculated as 11.17% of the subject’s mass (de Leva, 1996). The radius of gyration was calculated as 58.7% of the segment length of the pelvis (de Leva, 1996). Maximum angular momentum of the lower trunk was then calculated as moment of inertia of the lower trunk multiplied by angular velocity of the lower trunk.

The inverse dynamics technique was used to calculate joint forces (Equation 3-6) (Hirashima et al., 2008; Lu & O'Connor, 1999; Rao, Amarantini, Berton, & Favier, 2006). The baseball used in the study was weighed using a scale, and had a mass of 0.14178 kg. The baseball center of mass accelerations (x, y, and z), forearm center of mass accelerations (x, y, and z), and upper arm center of mass accelerations were calculated by MotionSoft from the digitized videos (accelerations at ball release). The acceleration due to gravity was assumed constant at 9.81 m/s. The mass of the hand was calculated as 0.61% of the subject's mass, the forearm mass was calculated as 1.62% of the subject's mass, and the mass of the upper arm was calculated as 2.71% of the mass of the subject (de Leva, 1996). The inverse dynamic procedure was used to calculate the force the ball applied to the hand at release as:

$$F_{bh} = (-m_b \times a_b) + (m_b * g) \quad \text{(Eqn 3)}$$

where: $F_{bh}$ was the force vector of the ball applied to the hand, $m_b$ was the mass of the ball, $a_b$ was the acceleration vector of the ball, and g was the gravitational acceleration vector.

The force applied to the wrist by the hand was calculated as:

$$F_{hw} = F_{bh} + (-m_h \times a_h) + (m_h * g) \quad \text{(Eqn 4)}$$

where: $F_{hw}$ was the force vector of the hand applied to the wrist, $F_{bh}$ was the force vector of the ball applied to the hand, $m_h$ was the mass of the hand, $a_h$ was the acceleration vector of the hand, and g was the gravitational acceleration vector.

The force applied to the elbow by the forearm was calculated as:

$$F_{fe} = F_{hw} + (-m_{fa} \times a_{fa}) + (m_{fa} * g) \quad \text{(Eqn 5)}$$

where: $F_{fe}$ was the force vector of the forearm applied to the elbow, $F_{hw}$ was the force vector of the hand applied to the wrist, $m_{fa}$ was the mass of the forearm, $a_{fa}$ was the acceleration vector of the forearm, and g was the gravitational acceleration vector.

The force applied to the shoulder by the upper arm was calculated as:

$$F_{us} = F_{fe} + (-m_{ua} \times a_{ua}) + (m_{ua} * g) \quad \text{(Eqn 6)}$$

where: $F_{us}$ was the force vector of the upper arm applied to the shoulder, $F_{fe}$ was the force vector of the forearm applied to the elbow, $m_{ua}$ was the mass of the upper arm, $a_{ua}$ was the acceleration vector of the upper arm, and g was the gravitational acceleration vector.

The resultant shoulder joint forces were resolved into the local reference frame using direction cosines of the upper trunk reference frame relative to the global reference frame to calculate compression and shear components.

**Statistical Analysis**

For statistical analyses, SPSS version 22 was used (IBM, Chicago, IL). A one-way ANOVA was conducted to ensure consistency among testing sites. The mean absolute difference, Cronbach's alpha, and intraclass correlation coefficients of maximum lower trunk angular momentum, shoulder joint anterior shear force at release, shoulder joint compressive force at release, and release speed were computed for the re-digitized trials to assess measurement agreement and intra-rater reliability, respectively. Variance and coefficient of variation were computed for the different trials of the same subjects to assess the consistency of movement kinematics within subjects. A bivariate correlation was computed to determine the association between the maximum angular momentum of the lower trunk during the arm cocking phase and the shear force on the shoulder at ball release to test the first hypothesis. Another bivariate correlation was computed to determine the association between the maximum angular momentum of the lower trunk during the arm cocking phase and the compressive force on the shoulder at ball release to test the second hypothesis. A re-sampling, bootstrapping method was employed to determine uncertainty in the bivariate correlations associated with the measurement error while avoiding assumptions about population distributions (Efron and Tibshirani, 1986). Ten new data sets with random differences in the study variables based on the mean absolute difference were created using random re-sampling with replacement. The bivariate correlations used to test the thesis hypotheses were calculated for the new datasets. The 95% confidence interval of the bivariate correlation was used as the uncertainty measure of the relationship (Ellison, Rosslein, and Williams, 2000). Bivariate correlations were also computed for additional study variables to determine if there were associations among: lower trunk angular momentum, shoulder joint anterior shear force, shoulder joint compressive force, and release speed (ball velocity). For this experiment the strength of the relationship was interpreted based on the correlation coefficient value obtained, in comparison to previous correlation coefficient values obtained by other similar overarm throwing research studies. For this study, the type I error rate was set as $\alpha = 0.05$ and the type II error rate was set as $\beta = 0.2$ (power = 80%). Based on previous similar research, correlation coefficients of approximately 0.5 were expected for this thesis (Huang, Wu, Learman, & Tsai, 2010; Sabick, Torry, Lawton, & Hawkins, 2004; van den Tillaar & Ettema, 2007). With error rates of 0.05 and 0.2, and anticipated correlation coefficients of 0.5, it was determined that a sample size of 23 participants was needed for statistical significance. Sample size power analysis was conducted with G*Power software (Heinrich Heine University Düsseldorf, Düsseldorf, Nordrhine-Westphalia, Germany).

# CHAPTER 4

## RESULTS

### Demographics and Descriptive Statistics

Descriptive statistics were computed for the entire sample size and the different testing sites (Table 1). The mean and standard deviations were computed for body mass, standing height, release speed (ball velocity), lower trunk angular momentum, shoulder joint anterior shear force (N), shoulder joint anterior shear force in bodyweights (BW), shoulder joint compressive force (N), and shoulder joint compressive force (BW) (Table 1).

A one-way ANOVA was conducted to ensure consistency among testing sites. Subjects at the West Virginia testing site were taller than subjects at New Jersey (1.89 m ± .07 vs 1.77 m ± .05, $F_{2,21}$ = 11.719, $p < .001$ ) (Table 1), and the subjects at Ohio were taller than the subjects at New Jersey (1.84 m ± .04 vs 1.77 m ± .05, $F_{2,21}$ = 11.719, $p = .009$ ) (Table 1). The subjects at the West Virginia testing site were younger than subjects at New Jersey (20.3 ± 1.1 vs 25.5 ± 3.3, $F_{2,21}$ = 11.971, $p < .001$) (Table 1), and the subjects at Ohio were younger than the subjects at New jersey (20.7 ± 2.1 vs 25.5 ± 3.3, $F_{2,21}$ = 11.971, $p < .001$) (Table 1). The subjects at the West Virginia testing site had a faster ball velocity than the subjects at New Jersey (34.3 m/s ± 1.6 vs 29.4 m ± 4.3, $F_{2,21}$ = 4.659, $p = .007$) (Table 1). There were no other significant differences among the testing sites.

The mean absolute difference (MAD) and its value relative to the study mean (RMAD), Cronbach's alpha (α), and intraclass correlation coefficients (ICC) of thesis outcome variables were computed for the re-digitized trials to assess measurement agreement and intra-rater reliability. Lower trunk maximum angular momentum values had moderate agreement (MAD = 0.020 kg.m²/s, RMAD = 6.4%), and exhibited strong reliability (α = 0.987, $ICC_{2,2}$ = 0.974).

Shoulder joint anterior shear force had poor agreement (MAD = 0.026 BW, RMAD = 21.7 %), and exhibited strong reliability ($\alpha$ = 0.944, $ICC_{2,2}$ = 0.894). Shoulder joint compressive force had moderate agreement (MAD = 0.031 BW, RMAD = 7.3%), and exhibited strong reliability ($\alpha$ = 0.991, $ICC_{2,2}$ = 0.981). Release speed had good agreement (MAD = 0.057 m/s, RMAD = 0.2%), and exhibited strong reliability ($\alpha$ = 0.991, $ICC_{2,2}$ = 0.981).

Variance and coefficient of variation were computed for the different trials of the same subjects to assess the consistency of the movement kinematics within subjects. Lower trunk maximum angular momentum had a variance of 0.020 kg.m$^2$/s and a coefficient of variation of 0.35%. Shoulder joint anterior shear force had a variance of 0.008 BW and a coefficient of variation of 1.48%. Shoulder joint compressive force had a variance of 0.004 BW and a coefficient of variation of 0.16%. Release speed had a variance of 1.817 m/s and a coefficient of variation of 0.04%.

| | Overall (Mean ± SD) | West Virginia (Mean ± SD) | Ohio (Mean ± SD) | New Jersey (Mean ± SD) | $F_{2,21}$ |
|---|---|---|---|---|---|
| Body Mass (kg) | 90.3 ± 13.9 | 94.7 ± 15.8 | 88.5 ± 9.9 | 88.5 ± 15.1 | 0.471 |
| Standing Height (m) | 1.82 ± .07 | 1.89 ± .07 | 1.84 ± .04 | 1.77 ± .05 | 11.719* |
| Age (years) | 22.8 ± 3.6 | 20.3 ± 1.1 | 20.7 ± 2.1 | 25.5 ± 3.3 | 11.971* |
| Experience (years) | 14.5 ± 4.2 | 12.4 ± 3.2 | 15.2 ± 2.6 | 15.5 ± 5.2 | 1.277 |
| Release Speed (m/s) | 31.6 ± 3.9 | 34.3 ± 1.6 | 32.4 ± 3.0 | 29.4 ± 4.3 | 4.659* |
| Lower Trunk Angular Momentum (kg.m²/s) | 0.313 ± .183 | 0.409 ± .129 | 0.330 ± .210 | 0.243 ± .180 | 1.972 |
| Shoulder Joint Anterior Shear Force (N) | 108 ± 97 | 117 ± 97 | 62 ± 33 | 128 ± 116 | 0.918 |
| Shoulder Joint Anterior Shear Force (BW) | 0.119 ± .100 | 0.120 ± .088 | 0.071 ± .036 | 0.144 ± .125 | 1.052 |
| Shoulder Joint Compressive Force (N) | 375 ± 125 | 439 ± 109 | 392 ± 126 | 327 ± 124 | 1.915 |
| Shoulder Joint Compressive Force (BW) | 0.423 ± .119 | 0.478 ± .120 | 0.446 ± .110 | 0.375 ± .115 | 1.889 |

**Table 1. Descriptive Statistics and F Values (ANOVA) for Variables and Testing Sites**
Note. F value shown with * indicates *p* values (< .05) with a significant difference.

## Hypothesis Tests

To test the first research hypothesis ($H_1$), a bivariate correlation was computed to determine the association between lower trunk maximum angular momentum during the arm cocking phase and shoulder joint anterior shear force at ball release. There was no association between lower trunk maximum angular momentum during the arm cocking phase and shoulder joint anterior shear force at ball release ($r = 0.149$, $p = 0.244$, 95% CI = $\pm$ 0.016) (Table 2) (Figure 4).

To test the second research hypothesis ($H_2$), a bivariate correlation was computed to determine the association between lower trunk maximum angular momentum during the arm cocking phase and shoulder joint compressive force at ball release. There was no association between lower trunk maximum angular momentum during the arm cocking phase and shoulder joint compressive force at ball release ($r = 0.222$, $p = 0.149$, 95% CI = $\pm$ 0.004) (Table 2) (Figure 5).

Bivariate correlations were also computed between lower trunk maximum angular momentum, shoulder joint anterior shear force, shoulder joint compressive force, and ball release to determine associations between the variables, which was done to assess the independence of the variables. There was no association between lower trunk maximum angular momentum during the arm cocking phase and release speed ($r = 0.171$, $p = 0.212$) (Table 2). There was no association between release speed and shoulder joint anterior shear force at ball release ($r = -0.055$, $p = 0.399$) (Table 2). There was a strong association between release speed and shoulder joint compressive force at ball release, indicating that as release speed increased shoulder joint compressive force also increased ($r = 0.520$, $p = 0.005$) (Table 2). There was no association between shoulder joint compressive force at ball release and shoulder joint anterior shear force at ball release (*r* = 0.089, *p* = 0.339) (Table 2).

| | Lower Trunk Angular Momentum ($kg.m^2/s$) | Shoulder Joint Anterior Shear Force (BW) | Shoulder Joint Compressive Force (BW) |
|---|---|---|---|
| Shoulder Joint Anterior Shear Force (BW) | 0.149 (0.244) | | |
| Shoulder Joint Compressive Force (BW) | 0.222 (0.149) | 0.089 (0.339) | |
| Release Speed (m/s) | 0.171 (0.212) | -0.055 (0.399) | 0.520 (0.005)* |

**Table 2. Bivariate Correlations among Independent and Dependent Variables**
Note. N= 24, *r* (*p*), significant *p* values are indicated with *.

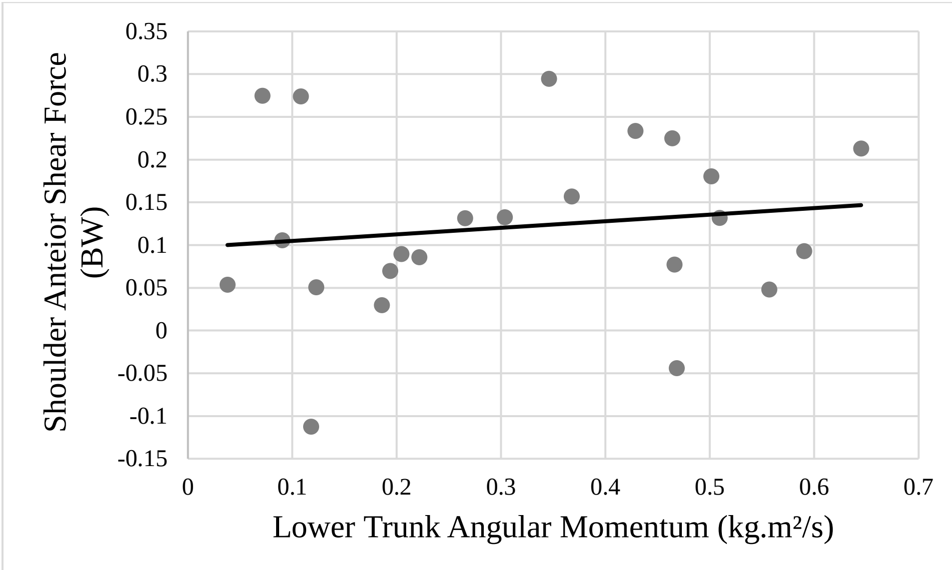


**Figure 4. Relationship between Lower Trunk Angular Momentum and Shoulder Joint Anterior Shear Force**

A scatter plot with line of best fit to demonstrate no relationship between lower trunk angular momentum (kg.m²/s) and shoulder joint anterior shear force (BW). $r = 0.149$, $p = 0.244$.

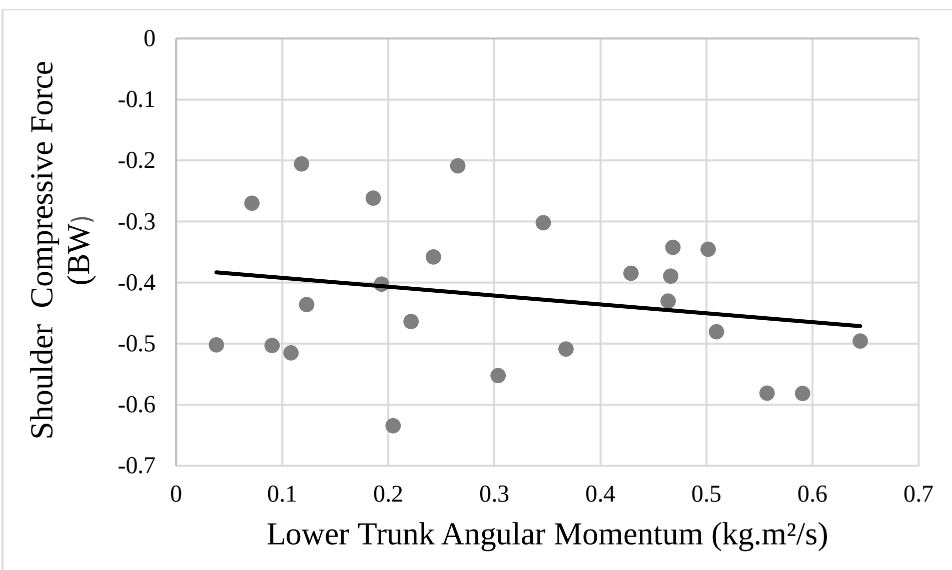


**Figure 5. Relationship between Lower Trunk Angular Momentum and Shoulder Joint Compressive Force**

A scatter plot with line of best fit to demonstrate no relationship between lower trunk angular momentum (kg.m²/s) and shoulder joint compressive force (BW). $r = 0.222$, $p = 0.149$.

# CHAPTER 5

## DISCUSSION

The purpose of this thesis was to explore the relationship between the angular momentum of the lower trunk and the throwing shoulder joint resultant compressive and shear forces during the overarm throwing motion of baseball athletes. The first research hypothesis developed to test the relationship between lower trunk angular momentum and shoulder force was that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint anterior shear force at ball release of the overarm throwing motion. This hypothesis was not supported, as maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase was not associated with the throwing shoulder joint anterior shear force at ball release of the overarm throwing motion ($r = 0.149$, $p = 0.244$) (Table 2) (Figure 4). Lower trunk angular momentum is not determinative of shoulder joint anterior shear force when measured discretely in this study's subject population.

The second research hypothesis developed to test the relationship between lower trunk angular momentum and shoulder force was that there would be a negative correlation between the maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase and the throwing shoulder joint compressive force at ball release of the overarm throwing motion. This second hypothesis was also not supported, as maximum angular momentum about the superior-inferior axis of the lower trunk during the arm cocking phase was not associated with the throwing shoulder joint compressive force at ball release of the overarm throwing motion ($r = 0.222$, $p = 0.149$) (Table 2) (Figure 5). Lower trunk angular momentum is not determinative of shoulder joint compressive force when measured discretely in this study's subject population.

**Overarm Throwing Motion**

This thesis did not identify an association between the maximum angular momentum at the lower trunk during the arm cocking phase and the forces at the shoulder joint at ball release. One potential explanation that no association was found between the angular momentum at the lower trunk and the forces at the shoulder joint is that the subjects in this thesis were inefficient at transferring momentum. It is possible that the subjects were able to generate a large amount of angular momentum at the lower trunk, but were unable to direct the momentum toward the throwing target. For example, if the momentum was directed towards the non-throwing shoulder instead of the throwing shoulder, it would require the throwing shoulder to make up for the momentum that was not transferred properly which could result in the throwing shoulder absorbing more force, even though the lower trunk did generate a large amount of angular momentum (Seroyer et al., 2010; Young et al., 1996). If some of the subjects were efficient at transferring momentum, but some were not, it could cause the data to show no association.

Improper timing of the lower trunk in relation to the movement of the upper trunk and shoulder also could have resulted in the findings of this thesis. In the overarm throwing motion the body segment should begin to move as the adjacent body segment reaches maximum velocity (Putnam, 1993). If the timing of the body segments is inefficient, then a large amount of angular momentum can be generated but not transferred. For example, if the subject achieves maximum angular momentum at the lower trunk after the shoulder has already begun to move, that maximum angular momentum will not be transferred to the shoulder. Research identified that professional players did not exhibit a large difference in torque at the upper trunk than lower level athletes, but their timing was different which occurred later in the arm cocking phase much closer to when the shoulder began to accelerate (not early in the arm cocking phase or after the shoulder had already moved) (Aguinaldo, Buttermore, & Chambers, 2007). The improper timing of the trunk reduces the transfer of momentum to the shoulder, and increases the force applied to the shoulder (Oyama et al., 2014). If some of the subjects did exhibit proper timing, and some did not, it could again result in no association between the angular momentum at the lower trunk and the forces at the shoulder joint.

**Kinetic Chain**

An alternative possibility that no association was found between the angular momentum at the trunk and the forces at the shoulder is that the kinetic chain sequence does not exist. However, the kinetic chain sequence exists, as it is supported by considerable research. The shoulder and upper arm alone are not able to produce the force that is needed to throw a baseball at a high velocity (Fleisig et al., 1995; Pappas et al., 1985; Roach & Lieberman, 2014). If the shoulder and arm cannot generate the force on their own, then it must come from somewhere else in the body. In both baseball and handball the more experienced and efficient athletes are able to better utilize and transfer ground reaction force which results in more force being applied to the ball (increased ball velocity) (MacWilliams et al., 1998; Rousanoglou et al., 2014). A higher ground reaction force at the push-off foot and the lead foot during the stride phase is associated with an increase in wrist and ball velocity (Alexander, 1991; MacWilliams et al., 1998; Young et al., 1996). From the legs, the force is then sent to the lower trunk, which has been identified as the power generator of the body, taking the load off of the shoulder musculature (Burkhart et al., 2003). Roach and Lieberman (2014) identified that the rapid accelerations of the distal segments (wrist and elbow) were generated by the power produced by the proximal segments such as the shoulder and trunk. Trunk flexion and rotation had a positive relationship with shoulder moments which indicated that the actions of the lower trunk and upper trunk are strongly related to throwing performance especially at the shoulder (Oliver, 2014). A greater average lower trunk velocity and a greater average upper trunk velocity during the arm cocking phase resulted in a higher ball velocity (Stodden et al., 2005). It has also been identified that the upper trunk generates and receives rotational force from the lower trunk, generates force by leaning forward, works to absorb some of the force towards the end of the throwing motion, and has an important role in maintaining stiffness in the muscles which transfers force by releasing elastic stored energy to the shoulder (McGill & Hoodless, 1990; Oliver, 2014; Santana et al., 2015; Stodden et al., 2005; Young et al., 1996). Since there is strong evidence that the actions of the lower body are connected to the actions of the upper body, it is likely the kinetic chain sequence does exist, and was not the reason that no association was found between the angular momentum at the lower trunk and the forces at the shoulder.

**Shoulder Joint Forces**

The shoulder joint anterior shear force at ball release calculated for this thesis had a mean value of 108 N, which is about 12% of body weight (0.119 BW ± 0.100). Previous research investigating anterior shear force at the shoulder reported the force as approximately 100 N at ball release, which agrees with the findings of this thesis (Feltner & Dapena, 1986; Fleisig et al., 1995).The mean shoulder joint compressive force at ball release in this thesis was 376 N, or approximately 42% of body weight (0.423 ± 0.119 BW). Previous research calculated shoulder joint compressive force to be around 860 N at ball release and closer to 95% of body weight (Feltner & Dapena, 1986; Fleisig et al., 1995; Werner, Gill, Murray, Cook, & Hawkins, 2001). The compressive force calculated by this thesis may be different from previous research for a few reasons. The calculations used to obtain force at the shoulder in this thesis, and previous research was similar, but the protocol and subject population was different. The previous researchers used professional and college pitchers only, compared to this thesis which used subjects that played at the professional, college, and high school level (Feltner & Dapena, 1986; Fleisig et al., 1995; Werner et al., 2001).

An athlete at a lower level of play may be less efficient at generating and transferring force, so the population I investigated may have generated less force or generated the maximum force before ball release (not efficient mechanically, slowing down before ball release). The previous investigators had mean release speeds of 40 m/s, 37.5 m/s, and 33.5 m/s, which are greater than the mean release speed for this thesis (31.6 m/s) (Feltner & Dapena, 1986; Fleisig et al., 1995; Werner et al., 2001). Higher ball velocity is often associated with a higher force, which was identified in this thesis as a significant correlation was found between release speed and shoulder distraction force ($r = 0.520$, $p = 0.005$) (Table 2). This thesis was also the first to investigate compressive forces from the non-pitching throwing motion in baseball. The previous studies investigated the pitching motion from a raised mound, where this thesis investigated a one-step throwing motion on flat ground (Feltner & Dapena, 1986; Fleisig et al., 1995; Werner et al., 2001). The differences in previous research compared to this thesis may explain the difference in the shoulder joint compressive force.

**Measurement Reliability**

Male subjects who currently play or played baseball were recruited and tested at three different locations on a baseball field in West Virginia (WV), in an indoor facility in Ohio (OH), and on a baseball field in New Jersey (NJ). There were no differences in thesis outcome variables among these locations. The only statistically significant differences in variables between locations were that the subjects from WV and OH were taller than the subjects from NJ, the subjects from WV and OH were younger than the subjects from NJ, and the subjects from

WV threw with a greater release speed than the subjects from NJ (Table 1). Age and height cannot be affected by the different testing locations. Release speed was higher in the WV subjects than the NJ subjects, because the WV subjects were division 1 collegiate athletes whereas the NJ subjects had a majority of athletes whose highest level of play was high school. There was adequate consistency among locations, meaning it was valid to analyze the study sample as a whole.

The re-digitized trials varied in measurement agreement. The mean absolute differences for lower trunk maximum angular momentum and shoulder joint compressive force demonstrated mean absolute differences of 6.4% and 7.3% of the mean study value, which indicates good intra-rater agreement. The mean absolute difference for shoulder joint anterior shear force demonstrated a mean absolute difference of 21.7%, which indicates poor intra-rater agreement. The intra-rater reliability of the re-digitized trials for lower trunk maximum angular momentum, shoulder joint compressive force, and shoulder joint anterior shear force were all strong, with values of Cronbach's alpha greater than 0.9 for each. The strong intra-rater reliability suggests that the differences in measurements were due to random errors, possibly attributable to the sampling rate and only being able to identify the critical instant of release to the nearest 0.017 seconds. The inability to identify a critical instant appears to be particularly impactful for the measurements of shoulder joint anterior shear force. The measurement errors had little effect on the relationships between lower trunk angular momentum and shoulder joint force. The bootstrapped correlation coefficients were of the same direction and similar magnitude to the initial data. The similarity among re-sampled data indicates that the relationships between discrete variables as determined by this thesis were not affected by measurement error.

The variance and coefficient of variation calculated among the different trials for the subjects were small, generally less than 1%, indicating that there was consistency of movement kinematics within subjects. That is, the subjects did not have much variance in their throwing motion from trial to trial. The small variance results do not necessarily mean that they were efficient, only that they were consistent. The subjects could have consistently inefficient mechanics, or consistently mis-timed their joint rotations, which does not contradict the first explanation of the findings of this thesis.

The mean maximum lower trunk angular momentum at arm cocking was 0.313 $kg.m^2/s$ for this thesis. This thesis is one of the first to report the lower trunk angular momentum during the arm cocking phase for baseball throwing. As angular velocity is a key component of angular momentum, the average angular velocity for this study was compared to previous research. The mean maximum lower trunk angular velocity for this thesis was 480 °/s (8.399 radians/s) which is similar to 490 °/s and 570 °/s reported in previous research (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Stodden et al., 2001).

An association was found in this thesis between release speed and shoulder joint compressive force ($r = 0.520$, $p = 0.005$), indicating that as release speed increased, so did the compressive force at the shoulder. Since release speed and compressive force at the shoulder exhibited a positive association, this may further indicate that the subjects had improper timing as Oyama et al. (2014) found that pitchers with improper trunk rotation sequence showed an increased force applied to the shoulder (Oyama et al., 2014).

It is unlikely that the power was too small to identify significant correlations. Before data collection, G*Power software was used, and 23 subjects were required to have a power of 80 percent ($r = 0.5$ and type I error rate was set as $\alpha = 0.05$). A sample size of 24 subjects was used which was larger than the 23 subjects needed to obtain a power of 80 percent. A significant correlation was found between release speed and shoulder joint compressive force ($r$ = 0.520, $p$ = 0.005) (Table 2). If the power was not adequate, it would be unlikely to find any significant correlations, and this correlation was of the magnitude predicted. Since the estimated required sample size for a power of 80 percent was smaller than the sample size used in the thesis, and a significant correlation was found, the reason for not finding a significant correlation between the angular momentum of the lower trunk and the forces at the shoulder is likely, not due to lack of power.

**Limitations and Future Directions**

There were several limitations present in this thesis. Some of the subjects were tested on a grass baseball field with visual cues, while some were tested at an indoor facility without the visual cues that would normally be present on a baseball field, and the indoor facility had a harder surface. The different facilities were compared to make sure they did not cause inconsistencies in the data collected, but it may be ideal to test all subjects at the same site to ensure the surfaces and visual cues are the same. Since the researcher only had the indoor testing site available for the Ohio group, this limitation could not be avoided. Anatomical landmarks were digitized on the subjects from the videos in Vicon Motus. All the videos were digitized by the same experienced researcher, but in some cases there was not a clear view of the landmarks in which the best estimate of the landmark had to be used. It is difficult to avoid small digitizing errors due to landmark obstruction. Another limitation of the thesis was that the phases and instants where the variables were selected, was done qualitatively by looking at the frames on the video. It is possible that the arm cocking phase or instant of ball release could be off by a frame or so. The inability to identify critical instants precisely is a limitation due to sampling frequency, but timing errors will be less than 0.017 seconds. This thesis also had a sample size on the smaller end (N = 24). It is possible that these 24 subjects are not representative of the entire larger population. When possible, a larger sample size is usually preferred in research.

There is one major suggestion recommended for future research. The variables used in this thesis were calculated as a maximum value during a phase, or at the instant of ball release. When examining the data there may have been inefficiencies in both timing and the transfer momentum exhibited by the subjects. For example, some of the subjects had maximum angular momentum of the lower trunk occur early in the arm cocking phase, and some of the subjects exhibited high accelerations at the shoulder before the hip reached maximum angular velocity, which would affect the association between the angular momentum of the lower trunk and the forces at the shoulder. Some of the subjects also began to slow their arm down before ball release which exhibited a smaller acceleration of the arm at ball release, hence exhibiting a smaller force at the shoulder (F=ma). For these reasons, it would be best to examine the variables during the entire throwing motion in a way that would allow for the influence of the amount and the timing of the force or momentum to be determined. Investigating the relationship between angular momentum of the lower trunk and forces at the shoulder during the entire throwing motion should provide more insight to the association between the variables.

**Conclusions**

In conclusion, there was no significant correlation between the maximum angular momentum at the lower trunk and the shoulder joint anterior shear force, or the shoulder joint compressive force at ball release. It is possible that no association was found due to inefficient timing and inefficient transfer of forces through the kinetic chain by the subjects tested. It is unlikely that no relationship exists, as previous research has provided evidence connecting movements of the lower trunk and shoulder, and identified the kinetic chain sequence (Feltner, 1989; Hirashima et al., 2002; Hirashima et al., 2008; Oliver, 2014; Roach & Lieberman, 2014). The depth and specificity of the results of this thesis demonstrates how important biomechanical research is to improving athlete performance and reducing injury risk. Researchers must be able to communicate their findings to coaches and athletes clearly. In the future it may be more beneficial to examine the variables throughout the entire throwing sequence, and identify the amount and the timing in which the momentum and forces occur at the different body segments.

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## APPENDIX A: OFFICE OF RESEARCH INTEGRITY APPROVAL LETTER

MARSHALL UNIVERSITY®

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**Office of Research Integrity**
Institutional Review Board
One John Marshall Drive
Huntington, WV 25755

FWA 00002704

IRB1 #00002205
IRB2 #00003206

November 5, 2018

Steven Leigh, Phd
Marshall University, School of Kinesiology

RE: IRBNet ID# 1314003-1
**At:** Marshall University Institutional Review Board #1 (Medical)

Dear Dr. Leigh:

| | | |
|---|---|---|
| **Protocol Title:** | [1314003-1] Angular Momentum of the Hip and Trunk in Overarm Throwing Athletes | |
| **Expiration Date:** | November 5, 2019 | |
| **Site Location:** | MU | |
| **Submission Type:** | New Project | APPROVED |
| **Review Type:** | Expedited Review | |

In accordance with 45CFR46.110(a)(4)(6)(7), the above study was granted Expedited approval today by the Marshall University Institutional Review Board #1 (Medical) Chair for the period of 12 months. The approval will expire November 5, 2019. A continuing review request for this study must be submitted no later than 30 days prior to the expiration date.

If you have any questions, please contact the Marshall University Institutional Review Board #1 (Medical) Coordinator Trula Stanley at (304) 696-7320 or stanley@marshall.edu. Please include your study title and reference number in all correspondence with this office.

## APPENDIX B: IRB AMENDMENT

MARSHALL UNIVERSITY

www.marshall.edu

**Office of Research Integrity**
Institutional Review Board
One John Marshall Drive
Huntington, WV 25755

FWA 00002704

IRB1 #00002205
IRB2 #00003206

March 1, 2019

Steven Leigh, Phd
Marshall University, School of Kinesiology

RE: IRBNet ID# 1314003-2
**At:** Marshall University Institutional Review Board #1 (Medical)

Dear Dr. Leigh:

| | | |
|---|---|---|
| **Protocol Title:** | [1314003-2] Angular Momentum of the Hip and Trunk in Overarm Throwing Athletes | |
| **Site Location:** | MU | |
| **Submission Type:** | Amendment/Modification | APPROVED |
| **Review Type:** | Expedited Review | |

The amendment to the above listed Expedited study was approved today by the IRB #1 Chair. The amendment is to change the population form from just Marshall baseball/softball athletes to all adult athletes who have played baseball/softball at a competitive level for at least three years. The updated recruitment flyer, email, and conversation has been approved.

If you have any questions, please contact the Marshall University Institutional Review Board #1 (Medical) Coordinator Trula Stanley at (304) 696-7320 or stanley@marshall.edu. Please include your study title and reference number in all correspondence with this office.

Sincerely,

Bruce F. Day, ThD, CIP
Director, Office of Research Integrity

## APPENDIX C: VITA

# Kevin D. Moore


**10 Normandy Drive**
**Wayne, New Jersey 07470**

Cell: (973) 997-9482
Email: kevinmoore2513@gmail.com


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***EDUCATION:***

**MARSHALL UNIVERSITY,** Huntington, WV — Expected Graduation: July 2019
MS Degree in **Biomechanics** — Current GPA 4.0

- Graduate Assistant
  - Teach and assistant undergraduate courses in biomechanics
  - Help students conduct research in the lab

**MONTCLAIR STATE UNIVERSITY**, Upper Montclair, NJ — May 2016

BS Degree in **Exercise Science** — Minor in **Business Administration** — Major GPA 3.5

- Dean's List
- Recipient of the Thelma Thompson Scholarship
  - Awarded to the student with the highest grade and achievement in the Measurement and Evaluation course
- Exercise Science Student Representative
  - One of three students selected to represent the MSU Exercise Science Program in an external department review
  - Met with visiting Exercise Science faculty from other universities and advised them on strengths and weaknesses of the MSU program

***CERTIFICATIONS / ORGANIZATIONS:***

- Completed the NIH (National Institutes of Health) web based training course for "Protecting Human Research Participants"
- CITI for Basic Course in Human and Medical Research
- Member of The International Society of Biomechanics (ISB)
- Member of The International Society of Biomechanics in Sports (ISBS)
- Member of The American Society of Biomechanics (ASB)

***RELATED EXPERIENCE:***

**Marshall University,** Huntington, WV — August 2017 - Present
Graduate Assistant under Dr. Suzanne Konz and Dr. Steven Leigh

- Teach and assistant teaching undergraduate courses
- Help undergraduate and graduate students conduct research
- Work in the lab using technologies including: EMG, Vicon Nexus, Vicon Motus, high-speed video cameras, video editing software, Cybex (isokinetic dynamometer), HR monitor, accelerometer, gyroscope, and force transducer
- Work with software including Kinovea and MotionSoft
- Work with MatLab

- Design study protocols

**American Sports Medicine Institute (ASMI),** Birmingham, AL October 2016 – June 2017
Student Researcher under Glenn Fleisig, Ph.D.

- Help with biomechanical evaluations of athletes
- Use technologies including force-plates, MotionAnalysis motion capture system, radar gun, and high speed video cameras, to help provide safer and more efficient biomechanical movements
- Input data into Microsoft Excel and Access
- Use programs written in C and MatLab to compute data
- Help prepare presentations and research articles
- Help place and remove reflective markers (used for MotionAnalysis mocap system) on specific anatomical landmarks

**Exercise Science Department at Montclair State University** December 2015 – August 2016
Research Assistant / Intern under Dr. Steven Leigh

- Work in EXSC lab using various technologies including Vo2 metabolic cart, HR monitors, EMG, 3D motion analysis equipment (electromagnetic), Biodex, Force-plates, and Kinovea.
- Help develop lab protocols and procedures.
- Use MatLab to analyze and interpret data retrieved from various Lab technologies.
- Use the data to evaluate sports performance, biomechanics, coordination, and to track progress during injury rehab.
- Produce written lab reports for patients.

**Wayne Physical Medicine and Rehabilitation Associates,** Wayne, NJ August 2014 – February 2015
Intern
- Assisted Physical Therapist by helping clients execute their rehab exercises
- Observed patients to make sure they performed exercises correctly and helped with heat or ice

**Research Experience**

- Dr. Leigh, Dr. Hosick, Vo2 Max Test for Paraplegic Athlete
    - Helped develop Vo2 max procedure for paraplegic athlete
    - Assisted in administering the test, using theVo2 metabolic cart and the HR monitor

- Professor Pigman, Rationale for using or not using the backpack with the hip strap attachment in the military
    - Assisted Professor Pigman by using 3-D motion analysis equipment, force plates, and a Vo2 metabolic cart to look at differences in two types of backpacks

- Dr. Leigh, Biomechanical issues for pitchers with shoulder injuries
    - Assisted Dr. Leigh by using 3-D motion analysis equipment and helping to video record the study to analyze the subjects' movements

- Independent Study, Difference in Biomechanical Movements and Landing Forces for Snowboarding Skills
    - Used a 3-D motion analysis system and force plates to evaluate several different snowboarding skills
    - Then used this information to look at the different biomechanical movements and forces involved in these skills in an attempt to make them more efficient or safer for the athlete

**Publications**

Fleisig, G. S., Diffendaffer, A. Z., Ivey, B., Aune, K. T., Laughlin, T., Fortenbaugh, D., . . . **Moore, K. D.**, Dugas, J. R. (2018). Changes in Youth Baseball Pitching Biomechanics: A 7-Year Longitudinal Study. *Am J Sports Med*, *46*(1), 44-51. doi:10.1177/0363546517732034

- Publication accepted for ISBS 2018 Conference and selected to present a ten minute oral presentation

***<u>OTHER ACCOMPLISHMENTS:</u>***

- Helped with data collection and processing for the USATF (United States of America Track and Field) during the 2018 Outdoor National Championships for men's and women's hammer throw in Iowa (June 2018)
- Participated in the USOC (United States Olympic Committee) Career and Development Fair in Colorado Springs, Colorado (Spring 2015)
- Attended the ASB (American Society of Biomechanics) annual conference in Raleigh, North Carolina (August 2016)
- Lifetime athlete and snowboard enthusiast

***<u>OTHER WORK EXPERIENCE</u>***

**Inserra Supermarkets, Inc. (Shop Rite),** Wayne, NJ January 2009 – August 2014
Front-End Manager, Customer Service Representative, Cashier

- Supervised up to 18 cashiers, including managing their work hours and breaks
- Assisted with register errors, opening and closing cash drawers for each shift
- Handled customer service issues and directed activities required throughout the store on a part-time basis
- Learned communication skills, how to work with the public, and how to accomplish goals as a team