The Effect of Stride Foot Contact Orientation on Overhand Shot Kinematics, Kinetics, and Performance Outcomes in Male Lacrosse Players

by

Matthew Michael Hanks

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Approved by

Gretchen D. Oliver, Chair, Associate Professor of Kinesiology
Wendi H. Weimar, Professor of Kinesiology
Sheri J. Thornburg-Brock, Associate Professor of Kinesiology
David M. Shannon, Humana-Germany-Sherman Distinguished Professor, Educational Research and Evaluation

Abstract

Lacrosse is one of the fastest growing team sports in the United States having increased from 253,931 players in 2001 to 826,033 players in 2016. Currently, there are no data regarding the kinematics and kinetics of the overhand lacrosse shot as they relate to shot velocity and accuracy. The purpose of this study was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, joint moment kinetics of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting. Fifteen male lacrosse players (16.60 ± 5.54 yrs.; 168.93 ± 16.14 cm; 63.05 ± 18.86 kg; 6.67 ± 3.39 yrs. experience) participated. Participants wore personal, protective equipment, and performed nine trials of the overhand shot on an unobstructed goal for maximal velocity and 36 randomized trials shooting at a target sheet for accuracy under three stride foot contact orientations: closed, in-line, and open. Results revealed significantly greater angular velocities of the pelvis, trunk, and upper extremities for the closed foot orientation, and ball velocity is highly correlated with angular kinematics. Additionally, this study revealed a significant tradeoff in shot velocity when prioritizing shot speed over accuracy. Lastly, increased ankle and knee moments were found across the stride foot orientations. These findings may prove beneficial for coaches, players, and researchers to further understand lacrosse shooting mechanics in an attempt to maximize performance, as well as potentially decrease injuries in the sport of lacrosse.

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CHAPTER I

INTRODUCTION

Lacrosse is perhaps the oldest team sport played in North America. Originally, the sport was played by Native Americans for ritualistic, exercise, and other practical reasons, such as celebrations, funeral ceremonies, settling disputes between and among tribes, as well as a tactic for war against European settlers attempting to seize Native American land.[1] Lacrosse was initially played on irregular fields up to two miles in length, with no boundaries, and with the number of players ranging from several to hundreds per team.[1] One of the first recorded matches dates back to 1721, and now, approximately 300 years later, lacrosse has become one of the most rapidly growing team sports in the modern United States.[1] According to the US Lacrosse Organization, national participation in lacrosse increased from 253,931 players in 2001 to 826,033 players in 2016.[2]

Lacrosse is a vigorous sport requiring athletes to be forceful yet agile, as it encompasses a variety of dynamic movements such as cutting, dodging, pivoting, and jumping. These movements are vital for avoiding defenders to achieve successful shooting. A well-executed lacrosse shot requires proper movement patterns of the legs, trunk, and arms; therefore, it is important to examine the entire human body when analyzing the overhand lacrosse shot.[3,4] While the sport has grown exponentially, there remains limited data regarding lacrosse shooting mechanics and factors that affect shooting performance. Studies that have investigated the kinematics of lacrosse shooting include exploring the various shot types on speed and accuracy,[4] kinematics as a function of arm dominance and playing experience,[5] overhand shot kinematics compared to the overhead throw,[6] and the effect of low back pain on overhand lacrosse shot kinematics.[7] Alterations of the stride foot contact orientation can affect an offensive player setting up for the shot, which may affect the kinematics and efficient execution of the overhand lacrosse shot. However, to the author's knowledge, there are no known data regarding the effect of stride foot contact orientation on lacrosse shooting mechanics.

As the sport of lacrosse has increased in participation, so has the incidence of injury. Knee and ankle injuries comprise the greatest portion of reported lacrosse injuries.[8-14] Of lacrosse injuries sustained at the knee and ankle joints, it is reported that the mechanism of injury is largely due to the non-contact, agile nature of the sport rather than contact with another player or stick.[8,10,12,13] One research study found that 25.9% of non-contact injuries occurred within 25 yards of the goal,[10] which is typically within the shooting range for many offensive players. As a large percentage of injuries occurring to the knee and ankle are non-contact and occur in the offensive zone, research is needed to investigate ankle and knee joint kinetics in an attempt to better understand lower extremity injuries likely sustained during the shooting motion.

The sport of lacrosse utilizes a stick to shoot the ball in an overhead motion; therefore, it is often considered a hybridization of an overhead sport and a stick sport. When examining mechanics in overhead sports, the majority of research focuses on the overhand throw,[15-17] the volleyball spike,[18] and the tennis serve.[19-23] Previous research investigating the mechanics of the overhead throw, volleyball spike, and tennis serve has found a positive relationship between angular velocities of the trunk and upper extremities and ball velocity.[15-23] These findings are in agreement with stick sports, such as golf and hockey, which have also found a positive relationship between angular velocities of the trunk and upper extremities and projectile velocity.[24-27] As lacrosse is a combination of these two sport types, exploring whole-body kinematics in overhead throwing and stick sports may provide insight into the biomechanics of the overhand lacrosse shot. However, the effect of foot orientation on projectile velocity in golf and hockey has not been assessed; therefore, relevant findings regarding the effect of foot contact orientation on angular kinematics are confined to overhead sporting tasks. Baseball pitching and throwing research has found that stride foot contact orientation is associated with upper extremity kinematics and kinetics. Specifically, an in-line foot contact orientation (facing the target) optimizes pelvis, trunk, and upper extremity angular kinematics and ball velocity, whereas a closed (toe-in) or excessively open (toe-out) foot orientation negatively alters pelvis, trunk, and upper extremity angular kinematics and decreases ball velocity.[15-17] As proper foot orientation is important in overhead throwing, it may also be important in the overhand lacrosse shot in optimizing trunk and upper extremity angular kinematics to maximize ball velocity.

Scoring a goal in lacrosse is a complex task. With the goalie encompassing the majority of the surface area of the goal, the offensive player is typically confined to shooting on the upper and lower corners of the goal. Additionally, the offensive player must use a high-velocity shot to prevent the goalie from tracking the ball and reestablishing defensive position to prevent the goal from being scored. Therefore, scoring requires the offensive player to shoot the ball with high velocity and great accuracy to bypass the goalie. Within the sport, there are three prominent lacrosse shot types used to score: sidearm, underhand, and overhand.[4] The sidearm and underhand shots are useful when attempting to score from a position that is to the side of the goal or around a defender with a high-velocity shot. The overhand shot is most useful in a scenario in which the offensive player is attempting to score on the goalie without the presence of a defender and accuracy of the shot is desired.[4] It has been found that sidearm shooting velocity is significantly greater than overhand and underhand shooting velocity; however, mean scores for accuracy are lowest for the sidearm shot and highest for the overhand shot.[4] These findings suggest the presence of a speed-accuracy tradeoff; however, this principle has not yet been examined within lacrosse shooting.

The investigation of a speed-accuracy tradeoff is not novel in sport, and this compromise between speed and accuracy has been investigated thoroughly in striking and stick-based sporting tasks, such as tennis,[22,28,29] hockey,[25-27,30] golf,[24,31,32] soccer,[33,34] as well as in throwing sports, such as baseball,[35-37] cricket,[36,38,39] handball,[40-42] and water polo.[43] The presence of a speed-accuracy tradeoff in sport remains unclear with some researchers agreeing with the existence of a tradeoff,[24-28,31-34,36,37,39,40,43] and others in disagreement;[22,29,30,41] however, no research has examined a speed-accuracy tradeoff in the overhand lacrosse shot. Identifying the presence of a speed-accuracy tradeoff may assist coaches in developing training methods to maximize scoring outcomes.

Goal scoring, within the sport of lacrosse, is an intricate task that emphasizes both speed and accuracy of the shot; therefore, it is important to identify mechanics that maximize performance outcomes, such as shot velocity and accuracy, as well as limit factors that inhibit performance or potentially result in injury. While the effect of foot contact orientation on segmental angular velocities, the relationship between segmental angular velocities and ball velocity, and a speed-accuracy tradeoff have all been separately examined in overhead and stick sports, it is to the author's knowledge that there are no data regarding these principles in lacrosse.

Purpose

The purpose of this study was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, joint moment kinetics of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting.

Significance

This research provided coaches, players, and parents with knowledge to optimize shooting velocity and accuracy, and theoretically gain an advantage in the rapidly-evolving sport of lacrosse. Furthermore, these findings are of importance to physicians and sports medicine professionals who seek to understand potential mechanisms for injuries sustained in lacrosse. This research sought to expand knowledge on lacrosse shooting mechanics and how to take preventative measures against developing chronic injuries in the sport.

Research Questions

RQ1: Does stride foot contact orientation affect the average angular velocities of the pelvis, trunk, and bilateral upper extremities during the phases of the overhand shot?

RQ2: Does stride foot contact orientation affect ball velocity?

RQ3: Is there a correlation between maximum angular velocities of the pelvis, trunk, and bilateral upper extremities and ball velocity during the phases of the overhand lacrosse shot?

RQ4: Is a speed-accuracy tradeoff present in the overhand lacrosse shot?

RQ5: How does stride foot contact orientation affect ankle and knee joint moments throughout the shooting motion?

Hypotheses

H_1: Angular velocities of the pelvis, trunk, and bilateral upper extremities were different between the three stride foot contact orientations: in-line, closed, and open.

H_2: Performing the overhand shot with an in-line stride foot contact orientation maximized ball velocity.

H_3: Angular velocities of the pelvis, trunk, and bilateral upper extremities had a strong, positive correlation with ball velocity.

H_4: The presence of a speed-accuracy tradeoff was observed in the overhand lacrosse shot.

H_5: Stride leg ankle and knee joint moments were greater in the transverse plane for the closed stride foot contact orientation compared to the in-line and open stride foot orientations.

Limitations

Limitations to the study include:

1. The lacrosse stick and ball were not tracked via electromagnetic sensors within the capture volume, thus the instant of ball release from the lacrosse stick was estimated using maximal dominant hand velocity as the kinematic indicator of ball release.
2. Lacrosse is a sport played on grass and turf surfaces, and players are required to wear cleats when playing; however, for this study, participants were asked to wear tennis shoes for indoor testing.

Delimitations

Delimitations for the study include:

1. Kinematic data were collected using a tethered electromagnetic tracking system.
2. Stride foot contact orientation was identified using tape aligned on the force plate.
3. Ball velocity was measured using a high-speed radar gun positioned behind the participant.
4. Shot accuracy was determined using a lacrosse goal shooting target sheet with four, equal quarter-circle target corners exposed.
5. Ball release was estimated by observing ball release in high-speed video captured at 240 frames/second and synchronizing it with the skeletal animations for seventy-nine shots from nine participants measured at 240 Hz. From this synchronization, maximal dominant hand velocity was indentified as a kinematic indicator of ball release and was used for all participants to estimate ball release.

Definitions

Kinematics: Area of study that examines the spatial and temporal components of motion (position, velocity, and acceleration).[44]

Kinetics: Study of the forces that act on a system.[44]

Speed-accuracy tradeoff: This theory states that the accuracy of an object in projectile motion is inversely related to the object's velocity.[37]

Launch Window: Introduced by William Calvin in 1983; states that there is a short, specific, and unique time frame in which an object must be released at a given velocity to ensure accuracy of the object at some distance.[45]

Summation of Speed Principle: The angular velocity of distal segments was magnified in sequential order due to movement being initiated from larger and more proximal muscles.[46]

Proximal-to-Distal Sequencing: States that the acceleration of the distal segment initially follows that of the proximal segment and then increases dramatically at peak velocity of the proximal segment. When the distal segment reaches peak acceleration, the proximal segment will be at a minimum.[47]

CHAPTER II

REVIEW OF LITERATURE

The purpose of this study was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, joint moment kinetics of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting. The objectives of this study were to assess differences in angular velocities of the pelvis, trunk, and upper extremities, ankle and knee joint kinetics, maximal ball velocity, and accuracy scores by as a result of altering stride foot contact orientation. The following chapter presents relevant literature addressing key aspects of the study. Moreover, this chapter is divided into five sections addressing the history, growth, and injury statistics in lacrosse, a speed-accuracy tradeoff within throwing and stick sports, the launch window hypothesis as a predictor of accuracy, angular velocities of anatomical segments as they relate to summation of speed and ball velocity, and an overview of lower extremity joint kinetics as they relate to loading and injury thresholds in sport.

History, Growth, and Injury Statistics in Lacrosse

Lacrosse is one of the oldest team sports in American culture. Dating back to the 18th Century, the sport was originally played by Native Americans for religious, ritualistic, and pragmatic activities, such as combat, settling land disputes, and memorial ceremonies.[1] Interestingly, at least three centuries since the first recorded match, lacrosse is one of the most rapidly growing sports in the United States.[2] According to the US Lacrosse Organization, national participation in lacrosse ranging from youth programs to post-college careers has increased from 253,931 athletes in 2001 to 826,033 athletes in 2016.[2] Of the 826,033 active lacrosse players, 812,788 (98%) play at the youth, high school, and collegiate levels, and of these athletes, 498,459 (61%) are male.[2] Similarly, the National Collegiate Athletic Association (NCAA) has reported increases in the national participation at the collegiate level, with the number of NCAA Men's Lacrosse athletes increasing from 6,551 athletes in 2001 to 13,446 athletes in 2016.[48]

These increases in lacrosse participation are thought to have led to increases in sport-related injuries. Of all reported injuries in lacrosse, knee injuries account for 7.1-20.3%,[8-14] ankle injuries account for 11.3-18.5%[8-14] with ankle sprains accounting for 87.5% of ankle injuries,[11] shoulder injuries account for 1.8-12.4%,[8-14] and elbow injuries account for 2.3-7.5%.[9,13] Of these injuries, sprains/strains account for 35-42.4% of injuries to the affected areas[8,9,12,13] with non-contact injuries (cutting, pivoting, and dodging) accounting for 15-50% of these injuries.[8,10,12,13] Additionally, as much as 25.9% of non-contact injuries occur within 25 yards of the goal,[10] which is within the shooting range for many offensive lacrosse players. Therefore, it may be possible that a significant number of injuries sustained while playing lacrosse, especially to the ankle and knee, occur during the preparatory shooting motion, as well as the full execution of the shot. While the epidemiology of lacrosse injuries is well documented, the origin of injury remains unclear. Previous literature documenting injuries has yet to distinguish between chronic and acute injuries, nor are normative kinematic data available for the overhand lacrosse shot to identify pathomechanics that may decrease performance or risk factors for potential injury. For these reasons, further research dissecting the overhand lacrosse shot should be conducted to provide players and coaches with the proper knowledge of mechanics for sport optimization and injury prevention.

Speed-accuracy tradeoff

A speed-accuracy tradeoff is adapted from a theoretical construct discovered by Paul Fitts in 1954.[49] Fitts' Law states that the rate of performance of a task is approximately constant over a range of movement and tolerance limits, and once performing a task outside of these ranges, the performance is hindered.[49] More recently, Fitts' Law has been adapted to physical and sport applications, specifically in regards to stick striking and throwing velocities as they relate to accuracy.[42,50] Moreover, Fitts' Law is the framework for the belief of an inverted relationship between thrown or kicked ball velocity and the accuracy of the ball, that is, a tradeoff between ball speed and ball accuracy. Despite numerous applications of Fitts' Law as it relates to a speed-accuracy tradeoff, it remains a controversial issue in sport research due to its complex nature. Within the parameters of a speed-accuracy tradeoff, researchers have found that the occurrence of this phenomenon is dependent on certain factors, specifically experience level and the task to be performed.[31,38,41]

In examining task experience, research has found that participants unfamiliar with a task are generally slower when performing the task, whereas those experienced with the task typically perform the task faster, and more fluidly.[51] In a study by Salthouse, the effect of age on speed and accuracy of a button-pressing task was investigated.[51] It was hypothesized that older and potentially less-experienced participants with the task, would perform slower to maximize accuracy.[51] They performed two experiments comparing speed and accuracy of a button-pressing task in young, middle-aged, and older adults.[51] In the first experiment, large correlations were found between age and accuracy for all groups, suggesting that a speed-accuracy tradeoff occurred regardless of age.[51] In an additional experiment, young (18-25 yrs.) and older (63-78 yrs.) individuals performed the same button-pressing experiment. Similar accuracy scores were found between the two groups at a moderate to slow reaction times, but that the older group was slower when performing the task, indicating a more prominent speed-accuracy tradeoff in older adults.[51] Research has found that novices typically succumb to a speed-accuracy tradeoff, but experts are able to maintain high levels of speed and accuracy when performing a task given their practice of the task.[22,29,31,41,42,52] More specifically, Beilock and colleagues investigated the effects of a speed-accuracy tradeoff in novice and experienced golf putters.[31] It was found that novice golf putters benefitted from more preparatory and movement time when attempting to accurately putt a golf ball; while the experienced golfers benefitted from less preparatory and movement time to accurately perform the same task. Thus, it was concluded that while a speed-accuracy tradeoff does occur in novices when performing a task, experts of the same task do not typically succumb to such a tradeoff,[31] and these findings have been found in other, more dynamic sporting tasks, such as handball shooting[41,42,52] and tennis striking.[22,29] In an examination of novice and expert team handball payers, Van den Tillaar and Ettema hypothesized a speed-accuracy tradeoff per their previous research.[40,41] Contrary to previous findings, it was found that experts were better when throwing for velocity and accuracy compared to the novices.[41] These findings are in agreement with Beilock and colleagues who found that inexperienced golf putters are slower and less accurate than experienced golf putters.[31] They believed that accuracy stayed constant, despite changes in ball velocities because shooting for speed and accuracy were well-practiced tasks by these players.[41] Specifically, they concluded that the task at hand, not experience level, tends to determine a speed-accuracy tradeoff.[41] This conclusion is in agreement with others who found that expert handball players had greater throwing velocities and accuracy scores compared to novice handball players when instructed to hit a moving target.[31,52] Similarly, when investigating a speed-accuracy tradeoff in team handball throwing, it was found that throwing velocity remained unchanged when prompting expert players to throw for accuracy, whereas throwing velocity significantly decreased when prompting novice players to throw for accuracy.[42] The authors concluded that this phenomenon occurred in sports where there is an emphasis of both speed and accuracy in the throw.[42]

Similar to the overhead throw, striking tasks have also been examined for a speed-accuracy tradeoff. For example, previous research has found that a speed-accuracy tradeoff does appear to occur in the tennis groundstroke between experienced and inexperienced players. It has been reported that elite tennis players were able to strike the ball during a groundstroke with increased hitting velocities without compromising accuracy, while sub-elite tennis players were unable to hit the ball accurately at a high velocity, indicating that experience may play a role in the speed-accuracy tradeoff in tennis hitting.[22] Similar conclusions were also found in the examination of female tennis player service accuracy.[29]

While some researchers have concluded that there does not appear to be a tradeoff between speed and accuracy in the sports of handball[41,42,52] and tennis,[22,29] others have found the opposite; that is, the presence of a speed-accuracy tradeoff in handball and other throwing sports (i.e., baseball, cricket, and water polo), as well as tennis and other striking and stick sports (i.e., golf, hockey). Moreover, most throwing research suggests that optimal throwing accuracy occurs at 70-80% of maximal throwing velocity; however, two studies report optimal accuracy as high as 88.1% and 92% of maximal throwing velocity during a throwing task.[35-43,53] Because throws executed at less than 100% maximal ball velocity resulted in higher accuracy scores, this research supports the notion of a speed-accuracy tradeoff in overhead throwing sports. Examining a speed-accuracy tradeoff in experienced team handball players, it was found that when experienced players were given a series of five instructive cues: i) throw the ball as fast as possible, ii) throw the ball as fast as possible and try to hit the target, iii) hit the target and throw the ball as fast as possible, iv) hit the target and try to throw as fast as possible, and v) hit the target, throwing velocity significantly decreased.[40] These findings agree with previous work by Garcia and colleagues that novice handball players were more accurate in throws where speed was not emphasized, thereby indicating a possible speed-accuracy tradeoff in the sport of handball, although it appeared to only occur in novice players.[42]

In addition to examining a speed-accuracy tradeoff in handball, the tradeoff has also been investigated in other sports, such as baseball pitching, cricket bowling, water polo, dart throwing, and other throwing tasks. A speed-accuracy tradeoff was observed when examining overhand ball throwing toward a target while gradually increasing ball speed.[35] It was concluded that balls thrown at 75% of maximal ball velocity were significantly more accurate than throws at 100% of maximal ball velocity.[35] Similarly, in a study examining the relationship between speed and accuracy in baseball and cricket players, it was found that baseball players threw the ball with greater speed and accuracy compared to cricket players; however, players from both sports experienced a significant speed-accuracy tradeoff.[36] Additionally, the baseball players had optimal accuracy when throwing at 70% of their maximal speeds, thus leading the authors to the conclusion that baseball players were more proficient throwers and claimed when accuracy is critical, ball speed should be decreased.[36] A similar study examining highly skilled junior-level baseball players found comparable results of a speed-accuracy tradeoff. When examining throwing at maximal and sub-maximal speeds, it has been found that baseball and cricket players were significantly more accurate when the throw was executed at 75-80% of their maximal throwing speeds.[37,39] When comparing the speed and accuracy of throws between baseball and cricket players, it was found that baseball players are able to throw more accurately at higher speeds compared to cricket players, but within each sport, accuracy and velocity were negatively correlated.[37,39] Furthermore, when examining velocity and accuracy between dominant and non-dominant arms of cricket players, it was found that throws with an emphasis on speed were faster than throws made with an emphasis on accuracy. It was also found that the dominant arms was better at throwing for accuracy than it was throwing for speed.[38]

Research has also examined a speed-accuracy tradeoff in water polo, a sport very similar to team handball. When examining Olympic female water polo players under instruction to throw a ball with maximal effort to a goal with a goalie and without a goalie present, a significant speed-accuracy tradeoff was observed. Specifically, water polo players threw at 90.1% of their maximal velocity when shooting on an empty goal; however, they only threw at 88.1% of their maximal velocity when shooting on a goal guarded by goalie.[43] Although the percentage of maximal velocity may only be slightly less in the goalie condition compared to the no goalie condition, the difference was significant, suggesting the possible, yet not obviously apparent, existence of a speed-accuracy tradeoff in water polo. These higher, yet sub-maximal velocities are in agreement with previous studies that found the most accurate throws typically occurred at 92% of the maximal throwing velocity.[53] While these values are higher than similar research,[43,53] the fact that accuracy scores were maximized at a sub-maximal throwing velocity suggests that a speed-accuracy tradeoff can occur in a variety of throwing tasks.

To the author's knowledge there are no data available investigating the speed-accuracy tradeoff in lacrosse shooting. Though lacrosse shooting can be an overhead movement similar to throwing in sports of handball, baseball, cricket and water polo; lacrosse shooting involves the addition of a stick. Given that the lacrosse shot is performed with a stick, it is equally important to analyze striking and stick sport movements, such as the tennis serve, golf swing, and hockey shot to rationalize the potential for shared mechanics that may allude to the presence of a speed-accuracy tradeoff in the overhand lacrosse shot.

While a few studies have investigated a speed-accuracy tradeoff in stick sports and found there was no relationship, more research has identified the likely presence of a speed-accuracy tradeoff in the tennis serve, golf swing, and hockey shot. However, there are conflicting results regarding a speed-accuracy tradeoff in tennis. When examining the overhead serve and groundstrokes under conditions in which the participants were required to hit a ball as fast as possible while still being accurate, two studies reported no presence of a speed-accuracy tradeoff,[22,29] whereas another study investigating the differences in the first and second tennis serves did find a speed-accuracy tradeoff.[28] Due to a need to maximize accuracy for the second serve and avoid losing the point outright, they hypothesized that the first "power serve" would have minimal spin and a higher velocity, whereas the second serve would be a "slice" or "topspin" serve performed at a slightly slower velocity.[28] It was found that the second tennis serve was performed using a slower serve velocity than the first serve. Specifically, the second serve was 24.1% slower than the first serve, and this is consistent with previous research identifying ball velocities of 70-80% to be the most accurate.[35-43] These findings suggest that when accuracy is the desired outcome, such as in the second tennis serve, ball velocity is decreased which is consistent with Fitts' Law and a speed-accuracy tradeoff.[49]

The tennis serve is an overhead movement and perhaps most reflective of the overhand shot mechanics in lacrosse; however, trunk rotation kinematics and the use of longer sticks in the golf swing and hockey slap and wrist shots suggest that research investigating a speed-accuracy tradeoff in these sports may also be important in an attempt to identifying a tradeoff between speed and accuracy in the lacrosse shot. When examining novice golf players, it was found that performing a putting task with an emphasis on accuracy significantly decreased the velocity and time of preparatory movement.[31] Additionally when examining consistency of putting and chipping accuracy tasks, it was found that slower and more controlled backswings decreased the amount of segmental variability during the movement and typically resulted in a more accurate shot.[24,32] The notion that a decrease in backswing velocity can elicit a more accurate shot yields further support for a speed-accuracy tradeoff, such that when the speed of the movement, rather than the speed of a ball, decreases, the accuracy of a golf shot increases.

Perhaps the most similar sport to lacrosse in terms of game play, strategy, scoring, and protective equipment is hockey, and therefore a speed-accuracy tradeoff in hockey may justify a similar speed-accuracy tradeoff in lacrosse shooting. Much like tennis and golf, as well as baseball, cricket, handball, and water polo, research investigating shot performance in hockey has found the existence of a speed-accuracy tradeoff.[25-27] Hockey research examining a speed-accuracy tradeoff has focused on the wrist and slap shots, with the wrist shot being considered the most accurate shot utilized.[25-27] When comparing shot type speeds, one study found that the average speed of a wrist shot was between 37-39m/s and the slap shot was between 42-46m/s;[27] while another other study revealed that a wrist shot was typically 20m/s, and the slap shot was typically 30m/s.[25,26] Despite the differences in reported values, these findings are in agreement that wrist shots have a lower velocity shots than slap shots. More specifically, it has been found that the wrist shot is 40% slower than the slap shot indicating that the slower shot is more accurate and further alluding to a speed-accuracy tradeoff.[27] In regards to actual measures of accuracy and performance outcomes, previous research has found that hockey players typically utilized slower slap shot velocities when shooting on the more difficult top right and left corners of a goal, yet the same participants utilized greater slap shot velocities when shooting on the less difficult bottom right and left corners of the goal.[25]

Striking and stick sports are complex and require the athletes to use implements as an extension of the human body. Beyond physiological proprioception, the athlete must know the position, velocity, and acceleration of the implement in space, and how to modify their physiological mechanics in attempt to execute a fast, yet accurate task. This ability is imperative in stick sports as the targets and margins for error when scoring are typically smaller. For example, scoring in golf is dictated by accurately putting a ball into a small hole, tennis service requires the server to place the ball into roughly a quarter of the court, and hockey and lacrosse scoring requires an offensive player to shoot a projectile into a goal that is defended by a mobile goaltender wearing protective equipment. Specifically in lacrosse, the goaltender utilizes a long stick with a wide net on the top end to defend the exposed goal around their shoulders. Ideally, an offensive player would shoot the ball with high velocity and accuracy; however, depending on the situation of the game or presence of a defender, this may not be an option. Therefore, the offensive player must decide instantaneously if they will shoot using high velocity or high accuracy to bypass the goaltender. For this reason, it seems likely that a speed-accuracy tradeoff exists in the overhand lacrosse shot.

The Launch Window as a Predictor of Accuracy

A common hypothesis examined when investigating throwing for accuracy is the launch window. Specifically, it is hypothesized that when throwing for accuracy, there is a specific launch window that results in the most accurate outcomes.[45] This hypothesis posits that there is a short, specific, and unique time frame in which an object must be released, at a given velocity, to ensure accuracy of the object at some distance.[45] Moreover, the closer the target and less accuracy required to hit that target, the larger the time frame to release the ball for a desired outcome (i.e., accurately hitting the target). Conversely, the farther the target is away from the individual throwing the ball, the smaller the time frame to release the ball for a desired outcome.[45] The launch window hypothesis was introduced in an attempt to understand the evolution of the human species and our abilities to throw objects for hunting and survival.[45] Recently, the launch window hypothesis has been adapted for physical and sports application, specifically when analyzing throwing sports. Similar to Fitts' Law, while the notion of proper timing is plausible for optimizing accuracy; recent research is inconclusive on the existence of a launch window with some data suggesting timing of anatomical segments and finger opening when releasing a ball is the key factor for maximizing accuracy,[37,53-56] and other data suggests that timing in these segments is not the key factor in maximizing accuracy.[57,58]

Research examining the optimal timing of finger opening as it relates to velocity and accuracy of throwing suggests that variability in timing of finger extension could be an important factor influencing the direction, velocity, and accuracy.[54] Additionally, 10ms variability was found in the timing of finger opening in 95% of the throws, indicating that timing within 10ms may optimize throwing accuracy.[54] Additionally, when examining the errors in the control of joint rotations associated with inaccurate overarm throws, similar results were found.[55] It was concluded that accurate overarm throwing required precise control of joint rotations for the ball to be released at the appropriate time, with inaccurate throws being the result of errors in control of those joint rotations.[55] Thus, it is suggested that accurate ball throwing is a result of finger opening timing with adjacent joint rotations, whereas inaccurate ball throwing is a result of inappropriate finger timing. Similar research has examined the optimal timing for muscle activations and release of a projectile.[53,56] Results revealed that neural timing circuits within 2-3ms yielded accurate projectiles hitting the target, thus precise finger muscle activation timing was necessary to elicit an accurate, fast throw.[53,56] More recently and perhaps most important to sport performance was an investigation of the launch window in relation to the speed-accuracy tradeoff in baseball throwing.[37] It was found that there was a significantly reduced launch window when participants performed throws at 100% compared to 80% of maximal throwing speeds. Thus indicating that as throwing speed increased, the time available to optimally release the ball and have it hit the target was diminished.[37] This trend is consistent with a speed-accuracy tradeoff and Fitts' Law, such that as one variable increases (i.e., ball velocity, throwing distance), the other variable under investigation (i.e., accuracy) tends to decrease, which suggests that throwing velocity may exhibit an Inverted U relationship with other variables in question.[49]

While some researchers have sought to prove that the launch window has merit in the sports realm, others have found that launch windows do not function in the manner previous researchers have hypothesized and that ball release timing is not the main factor in determining the accuracy of a throw.[57,58] It has been documented that throws occurring outside the 10ms launch window account for 5% of inaccurate throws.[54] Thus, it has been postulated that inaccurate throws could be attributed to factors other than timing, such as variability in amplitude and velocity of finger extension and variability in the height of the hand trajectory.[54] Additionally when examining launch window and movement variability in dart throwing, it was found that hand movement error still allowed for accurate throws.[57] Therefore, it was suggested that the ability to compensate for movement variability determines accuracy of a throwing task.[57] Last, when examining the timing of ball release and accuracy in overarm throws performed by skilled and unskilled individuals, it was found that, while variability in the timing of ball release can affect ball speed, it only seemed to have an influence on unskilled throwers.[58] Researchers also found that ball speed variability in skilled throwers is primarily due to arm speed variability rather than variability in timing of ball release.[58]

Due to humans' innate ability to adapt to changes in proprioception, it seems likely that accuracy can be maintained under conditions of movement variability and increased degrees of freedom.[57] [58] However, it also seems plausible that accuracy is largely dependent on finely-tuned neuromuscular control and timing.[53-56] Because of the uncertainty of a launch window in baseball, which is one of the most popular sports in the world, it should not be surprising that the launch window has not been evaluated in lacrosse. Given that lacrosse shooting requires angular mechanics of the stick to produce a tangential and linear ball release, it does support the notion that a launch window in lacrosse may be beneficial. However, there are many variables that would compromise the launch window, and these variables can greatly differ between lacrosse players. For example, offensive players use lacrosse sticks that are shorter than sticks used by defensemen, therefore the angular mechanics of a shot using a short stick would be different than those used when shooting with a long stick. Perhaps the most important factor that would influence a possible launch window would be the personalization of the lacrosse stick mesh. Depending on how the mesh is laced, where the shooting strings are inserted, and how tight the shooting strings are woven, can greatly affect the ball release from a lacrosse stick. For example, tight shooting strings cause an earlier ball release and a lower trajectory from the stick, whereas looser shooting strings allow a later ball release and a higher trajectory from the stick. Another contributing factor to launch windows in lacrosse shooting is the shot type. Overhand, sidearm, and underhand shots utilize different trunk, lower, and upper extremity kinematics.[3] Overhand shots produce a high ball release in which the ball can only drop due to the force of gravity. Sidearm and underhand shots; however, can be performed to drop or rise depending on the orientation of the stick at ball release. Experienced lacrosse players will rotate the shaft of the stick up or down using their fingers just prior to ball release to produce a shot that rises, stays level, or drops (similar to baseball and softball pitching).

Summation of Speed and Ball Velocity in Overhead and Stick Sports

The summation of speed principle was coined in 1972 by researchers who determined that distal segments have greater angular velocities than proximal segments in throwing and kicking tasks.[46] More specifically, the angular velocity of the distal segments is magnified in sequential order due to movement being initiated from larger, stronger, and more proximal segments and having the energy transferred to the smaller, distal segments. This maximizes energy transfer through the kinetic chain and decreases forced placed on smaller, distal segments to generate the movement.[46,59] This principle is very similar to proximal-to-distal sequencing, which states that the acceleration of the proximal segment causes the distal segment to lag behind. Next, the distal acceleration is magnified as a result of the proximal acceleration, while the proximal segment is then slowed down by the movement of the distal segment.[47] These two principles rationalize much of what is known about angular velocities and accelerations in overhead throwing and striking tasks, such as baseball throwing[17,60-64] and the tennis serve,[20,28,65-67] as well as stick sports that require trunk rotation to perform a task, such as golf[32] and hockey.[26,30]

Proximal-to-distal sequencing has been found to be vital for optimal throwing mechanics and ball velocities in baseball pitching.[17,60-64] Fleisig et al. identified that trunk and hip separation are important for initiating the stretch-shortening cycle, which they posit allows for greater upper arm, forearm, and hand velocities to throw a ball with a greater velocity and force.[60-63] These findings are in agreement with other research that found the importance of trunk rotation in producing effective and forceful throws in baseball.[17,64] Similar to the overhand throw, previous research investigating the tennis serve suggests the importance of proximal-to-distal sequencing. Specifically, studies have found that large trunk rotation angular velocities are vital for producing a high-velocity serve, which is desired in the first tennis serve that emphasizes speed and power.[20,67] However, in the second serve where the ball must land in play to avoid losing a point and therefore emphasizes accuracy, researchers found that tennis players serve closer to their bodies and decrease the amount of rotation that occurs. By using these altered mechanics, researchers posit that the tennis serve velocity decreases by 24.1% to favor accuracy instead of ball velocity and power.[28] Additionally, Hume et al. reported that hip and trunk separation during the downswing greatly increases ball velocity in the golf swing.[32] The rationale of hip and trunk separation is based on the stretch-shortening cycle, which is thought to explain proximal-to-distal sequencing occurring during this part of the motion. Additionally, a trend in angular segmental velocities in professional golfers of 498°/second for the hips, 723°/second for the shoulders, 1165°/second for the arm, and 2090°/second for the club head was reported.[32] Similar to the golf swing, studies have identified several variables that appear to be predictors for hockey shot accuracy.[25,26] Like golf, researchers suggest that trunk and pelvis rotation allow for segmental separation, which increases the storage and utilization of elastic potential energy during a stretch-shortening cycle. They also suggest that less accurate shooters showed greater movement and less control through the trunk, indicating inefficient energy transfer from the lower body to the upper body. Similarly, they found that more accurate shooters showed more stability in the trunk and more variable control over the distal segments in the lead/shooting arm,[25,26] which agree with previous findings that more distal joints control the final trajectory of an object.[53-56] Interestingly, Frayne and colleagues found no correlation between angular velocity and accuracy, unlike the work of Michaud-Paquette et al. who found greater angular velocities were associated with less accurate shots.[30] Lastly, it has been suggested that the overhand lacrosse shot may utilize the stretch-shortening cycle in the bilateral elbow flexors and extensors during the cocking phase to produce a high-velocity shot.[3] Given that previous research has found the stretch-shortening cycle and summation of speed in overhead throwing and other striking tasks, it is important to examine these principles in lacrosse in an attempt to explain the high-velocity overhand lacrosse shot.

Lower Extremity Joint Kinetics

Mercer and Nielson described the first two phases of the overhand lacrosse shooting motion pertaining to adequate footwork to set up the individual for the shot.[3] For this reason, understanding the kinetics at the ankle and knee when preparing for a shot may be worthwhile to understand the basis for kinetic chain energy transfer throughout the shot. Likewise, it may also provide insight into the high injury rates of the ankle and knee in lacrosse. Understanding ankle and knee joint injuries are complex given the various mechanisms that can result in injury. Despite the complexity of the mechanisms, research has attempted to determine ankle ligament failure thresholds[68-74] and knee ligament failure thresholds.[75-81] Previous research has found ligament failure and joint injury at ankle joint moments of 36.2-210 Nm.[68-74] Research has yet to investigate the effect of stride foot orientation on ankle joint moments in the overhand lacrosse shot, which may or may not elicit values near these reported injury thresholds. In regards to the knee, it is reported that the anterior collateral ligament (ACL) is capable of withstanding linear forces between 630-2,275 N before failure;[75-81] however, joint moments about the knee are not commonly reported. Again, there is a lack of data available regarding the effect of stride foot orientation on linear or angular knee joint kinetics in the overhand lacrosse shot. Observations of joint moments approaching these reported injury thresholds could provide evidence for coaches to determine if lacrosse players use certain mechanics in specific game situations that may predispose them to possible acute injury.

From the paucity of literature, it is clear that the biomechanics of lacrosse shooting are not well reported. While overhand throwing and striking sports provide some insight for estimating the biomechanical nature of lacrosse shooting, there may be significant kinematic differences that suggest lacrosse shooting mechanics are unique and specific to the sport. Therefore, more extensive research should be conducted to accurately identify mechanics used in the sport. Specifically, data regarding proper kinematics and kinetics for sport optimization, in terms of maximizing shot velocity and accuracy, are vital for the continued growth and intensity of the sport. Should certain kinematic and kinetic variables reflect greater shot velocities and accuracy, it is prudent that researchers and coaches recognize and implement these into training protocols. Similarly, increases in national participation and associated instance of injuries illustrates a need for greater understanding of pelvis, trunk, and upper extremity angular velocities, as well as lower extremity joint moments produced during shooting. By better understanding the kinematics and kinetics of lacrosse shooting, parents, players, and coaches can continue to improve this historical game in a safe and effective manner.

CHAPTER III

METHODS

The purpose of this study was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, as well as joint moments of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting. This chapter outlines and describes the methodology of the study. Sections describing the methodology include: 1) Participants, 2) Experimental Setting, 3) Instrumentation, 4) Design & Procedures, and 5) Experimental Design.

Participants

Fifteen male lacrosse players (16.60 ± 5.54 yrs.; 168.93 ± 16.14 cm; 63.05 ± 18.86 kg; 6.67 ± 3.39 yrs. experience) participated. Participants were required to be between the ages of 7 to 30 years with at least one year of competitive lacrosse experience playing at either the midfield or attackman positions, in good health, and free from injury or surgery for the past six months. This sample was chosen in an attempt to adequately reflect the general population of male lacrosse players in the United States. Participants completed a thorough health-history questionnaire to determine eligibility for the study (Appendix A). The following populations were excluded from the study: 1) female lacrosse players, 2) male defensemen and goaltenders, and 3) players who wear ankle or knee braces during competition for joint stability. Prior to participation, each participant signed an informed consent/assent document approved by the Auburn University Institutional Review Board (Appendix B). Participants the age of 19 years old or older provided consent to participate, whereas participants younger than 19 years old were required to obtain parental consent and minor assent. Sample size was determined via power analysis (G*Power 3.1),[82] and it was determined that 15 participants were needed to elicit a power of 0.80 and an effect size of 0.32 at α error probability ≤ 0.05.

Experimental Setting

Data collections were performed in a controlled laboratory setting inside the Sports Medicine & Movement Laboratory within the School of Kinesiology at Auburn University. This location contained the proper space, equipment, and supplies to fulfill the objectives of the study.

Instrumentation

Ball Velocity

Ball velocity (mph) was measured using a radar gun (Stalker Pro II Speed Sensor Radar, Applied Concepts, Inc./Stalker Radar, Richardson, TX) positioned directly behind the participant.[4,22,23,33,42,83]

Shot Accuracy

Shot accuracy was assessed using a lacrosse goal shooting target sheet with four, equal quarter circle target corners exposed (Under Armour Goal Blocker Lacrosse Goal

Shooting Target, Under Armour, Baltimore, MD). The area of each target was 1017.88 cm^2. ($A=\pi r^2/4$, r=36cm) (Figure 1).

Figure 1. Lacrosse target shooting sheet.

Ball Release

Ball release was assessed using a high-speed camera set to a frame rate of 240 frames/second (Casio EXILIM EX-FH25, Casio, Tokyo, Japan).

Kinematics & Kinetics

The MotionMonitor® (Innovative Sports Training, Chicago, IL) synced with an electromagnetic tracking system (trakSTAR Wide-Range, Ascension Technology Corp., Burlington, VT) was used to collect kinematic and kinetic data. Magnitude of error in determining the position and orientation of the electromagnetic sensor within a calibrated world was less than 0.02 m.[6] Kinematic data describing the position and orientation of the electromagnetic sensors were sampled at 240 Hz. Ankle and knee joint moments of the stride leg were normalized to the participants' mass. Joint moments were assessed in the transverse plane with counterclockwise indicating the positive direction and clockwise indicating the negative direction. Joint moments were calculated using forward dynamics equations within the MotionMonitor® software and were computed using previously validated anthropometric parameters.[84-86] Raw data were independently filtered along each global axis using a fourth order Butterworth filter with a cutoff frequency of 20.0 Hz.[6] A 40 cm x 60 cm forceplate (Bertec Corp, Columbus, OH) anchored into the floor was used as an event marker to determine foot contact of the stride foot. Force plate data was sampled at a rate of 1000 Hz.

Design & Procedures

Participants were asked to wear a personal, loose-fitting tee shirt, shorts, and tennis shoes for the duration of the study. Upon participant arrival to the laboratory for testing, they were asked to complete a thorough health-history questionnaire (Appendix A) to ascertain their ability to safely perform the study. Participants were also asked to sign assent (for minors and their parent/guardian) or consent (for adults) documents approved by the Institutional Review Board of Auburn University (Appendix B). Once assent/consent and health-history were obtained and suitability for participation in the study was determined, eligible participants had a series of 14 electromagnetic sensors (Flock of Birds, Ascension Technology Corp., Burlington, VT) affixed to the following anatomical locations: (1) seventh cervical vertebra (C7) spinous process; (2) pelvis at the first sacral vertebra (S1); (3-4) bilateral deltoid tuberosity of the humerus; (5-6) bilateral wrist on the dorsal aspect of the forearm 2 cm superior to the radial and ulnar styloid processes; (7-8) bilateral hand on the dorsal aspect of the third metacarpal; (9-10) bilateral midpoint of the lateral aspect of the femur; (11-12) bilateral shank centered between the head of the fibula and the lateral malleolus; and (13-14) bilateral feet on the dorsal aspect of the second metatarsal bone (Figures 2-6). Graduate student researchers trained in anatomical palpation, location, and application techniques assisted in affixing the sensors. Sensors were secured to the skin using generic double-sided tape coupled with Cover Roll (BSN Medical, Hamburg Germany) and PowerFAST cohesive tape (Andover Healthcare, Salisbury, MA) to ensure the sensors remained stationary throughout the testing process. An additional sensor attached to a stylus was used to digitize the trunk and upper and lower extremity bony landmarks (Table 1) to create a skeleton model of the participant.[87-89] Participants stood in an anatomical neutral position during digitization to accurately identify bony landmarks. A link segment model was developed through digitization of joint centers for the ankle, knee, hip, shoulder, elbow, wrist, twelfth thoracic verteba (T12) to the first lumbar vertebra (L1), and the seventh cervical vertebra (C7) to the first thoracic vertebra (T1). The spinal column was defined as the digitized space between adjacent spinous processes, and the ankle and knee joints were defined as the midpoint between the the digitized medial and lateral malleoli and the midpoint between the digitized medial and lateral femoral condyles.[6] The shoulder joint was digitized by palpating the acromioclavicular (AC) joint, as well as the anterior and posterior portions of the humeral head. The hip joints were estimated using the rotation method, which was performed by stablizing the the joint and passively moving the joint in 10 small, circular positions.[90] This method has been previously reported to provide valid positional data for the hip joint.[90] The hip joint center was calculated from the rotation of the femur relative to the pelvis. Varation in the measurement of the joint center (root mean square) was accepted for values less than 0.003 m.[6]

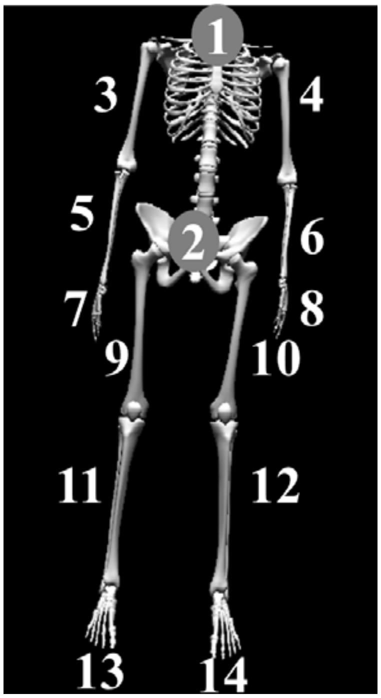


Figure 2. Electromagnetic sensor setup.

Figure 3. Posterior sensor placement without protective equipment.

Figure 4. Anterior sensor placement without protective equipment.

Figure 5. Posterior sensor placement with protective equipment.

Figure 6. Anterior sensor placement with protective equipment.

Raw data regarding sensor orientation and position were transformed to local coordinate systems for segments following International Society of Biomechanics recommendations.[88,89] Two points described the longitudinal axis of each segment, and the third defined the plane of the segment. The second axis was perpendicular to the plane, and the third axis was defined as perpendicular to the first and second axes. The world axes were defined with the y-axis in the vertical direction, the x-axis in the forward-facing horizontal direction, and z-axis to the right and perpendicular to the x-axis. Euler angle decomposition sequences via International Society of Biomechanics recommendations were used to describe the position and orientation of the body segments.[88,89] Specifically, ZX’Y” were used for the ankle, knee, pelvis, trunk, elbow, and wrist, and YX’Y” were used for the shoulder (Table 2). All data were synchronized passively via a data acquisition board and time stamped through The MotionMonitor®.

Table 1. Description of bony landmarks to be digitized.

Bony Landmarks	Digitized Bony Processes
Trunk	
Seventh Cervical Vertebra (C7)	C7 Spinous Process
Twelfth Thoracic Vertebra (T12)	T12 Spinous Process
Eighth Thoracic Vertebra (T8)	T8 Spinous Process
Suprasternal Notch	Most Cranial Aspect of Sternum
Xiphoid Process	Most Distal Aspect of Sternum
Humerus	
Medial Epicondyle	Medial Aspect of Humeral Epicondyle
Lateral Epicondyle	Lateral Aspect of Humeral Epicondyle
Forearm	
Radial Styloid Process	Lateral Aspect of Radial Styloid
Ulnar Styloid Process	Medial Aspect of Ulnar Styloid
Hand	
Third Metacarpalphalangeal Joint	Dorsal, Distal Aspect of the 3rd Metacarpal
Third Distal Phalanx	Most Distal Aspect of the 3rd Phalanx
Knee	
Lateral Femoral Condyle	Lateral Aspect of Femoral Condyle
Medial Femoral Condyle	Medial Aspect of Femoral Condyle
Ankle	
Lateral Malleolus	Lateral Aspect of the Distal, Fibular Head
Medial Malleolus	Medial Aspect of the Distal Tibia

Table 2. Euler angle decomposition sequence orientations.

Segment	Axis of Rotation	Angle
Ankle		
Rotation 1	Z	Dorsiflexion/Extension
Rotation 2	X’	Inversion/Eversion
Rotation 3	Y”	Internal/External Rotation
Knee		
Rotation 1	Z	Flexion/Extension
Rotation 2	X’	Varus/Valgus
Rotation 3	Y”	Internal/External Rotation
Pelvis		
Rotation 1	Z	Anterior Tilt/Posterior Tilt
Rotation 2	X’	Left Lateral Flexion/Right Lateral Flexion
Rotation 3	Y”	Left Rotation/Right Rotation
Trunk		
Rotation 1	Z	Flexion/Extension
Rotation 2	X’	Left Lateral Flexion/Right Lateral Flexion
Rotation 3	Y”	Left Rotation/Right Rotation
Shoulder		
Rotation 1	Y	Humeral Plane of Elevation
Rotation 2	X’	Humeral Elevation
Rotation 3	Y”	Internal Rotation/External Rotation
Elbow		
Rotation 1	Z	Flexion/Extension
Rotation 2	X’	Varus/Valgus
Rotation 3	Y”	Pronation/Supination
Wrist		
Rotation 1	Z	Flexion/Extension
Rotation 2	X’	Ulnar Deviation/Radial Deviation
Rotation 3	Y”	

Prime (‘) and double-prime (“) notations represent previously rotated axes due to the rotation of the local coordinate system resulting in rotation of all axes within the system. (Rotation about the x-axis also results in rotation of the y- and z-axes resulting a new system: X’Y’Z’. Subsequent rotations then occur about these axes.[88,89])

Following digitization, the participant donned all personal protective equipment they typically wore during a competitive lacrosse game, including a helmet, shoulder and elbow pads, gloves, and their personal, regulation lacrosse short-stick. Participants were given exactly five minutes to warm up shooting a standard-size lacrosse ball (5.0 oz.) into a regulation-sized lacrosse goal (182.88 cm high x 182.88 cm wide x 213.4 cm long, Maverik Lacrosse, New York City, NY) positioned at a distance of 5 meters. After completing the warm-up, participants were instructed to perform three maximal effort overhand shots accurately on an unobstructed goal under three stride foot contact orientation conditions: closed (<-10˚), in-line (-10 to 10˚), or open (>10˚) determined by tape indicators on the force plate for the position ranges. Reported angles were relative to the positive x-axis represented by 0˚, with negative angles to the right of the positive x-axis and positive angles to the left of the positive x-axis. Foot contact orientation angle for left-handed players were transformed to fit right-handed player data for ease of data analysis and interpretation. In the first set of three shots, participants were instructed to shoot with their stride foot landing entirely on the force plate in a closed foot contact orientation. The next set of trials were performed with the participant landing with their stride foot in an in-line foot contact orientation. The last set of trials were performed with the participants landing with their stride foot in an open foot contact orientation.

A successful trial included the participant performing the overhand shot with their stride foot landing in the correct foot contact orientation on the force plate, per the instruction of the researcher. Correct foot orientation was determined via visual inspection from the researcher, who determined the adequacy of the foot orientation, and was supported using foot orientation data provided via the electromagnetic sensor and the skeletal animation. Maximal ball velocity (mph) was measured using a radar gun (Stalker Pro II Speed Sensor Radar, Applied Concepts, Inc./Stalker Radar, Richardson, TX) positioned behind the participant,[4,22,23,33,42,83] and the average velocity of the three shots per set was calculated and used for baseline measurements that were compared to ball velocities when assessing for accuracy.

After baseline values for average maximal velocity were recorded for each foot contact orientation, a lacrosse goal shooting target sheet with four equal quarter circle target corners exposed (Under Armour Goal Blocker Lacrosse Goal Shooting Target, Under Armour, Baltimore, MD) was affixed to the goal to assess accuracy. To prevent learning, participants were randomly assigned the order of stride foot contact orientation and the target at which they shot. A random number generator (The Random Number Generator, Nicholas Dean Apps ©2013) was used to determine the sequence of shots to be performed. The following numbers corresponded to the foot contact orientation and target that were examined during the trial: 1) closed foot orientation - top left target, 2) closed foot orientation - top right target, 3) closed foot orientation - bottom left target, 4) closed foot orientation - bottom right target, 5) in-line foot orientation - top left target, 6) in-line foot orientation - top right target, 7) in-line foot orientation - bottom left target, 8) in-line foot orientation - bottom right target, 9) open foot orientation - top left target, 10) open foot orientation - top right target, 11) open foot orientation - bottom left target, 12) open foot orientation - bottom right target (Figure 7). A maximum of three trials per foot contact orientation per target were performed, resulting in twelve shots performed per foot contact orientation with a grand total of thity-six shots performed across all foot contact orientations during the accuracy assessment. Accuracy was scored with one point awarded for a shot that passed through the assigned target for that trial, whereas no points were awarded for a shot that missed the assigned target or passed through a different target.

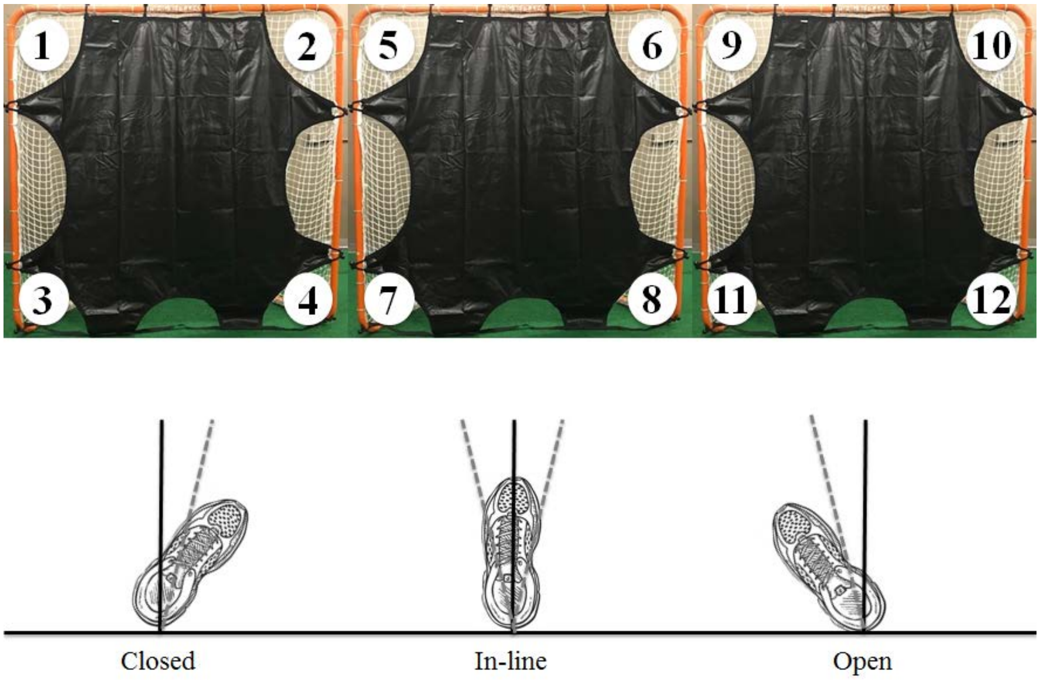
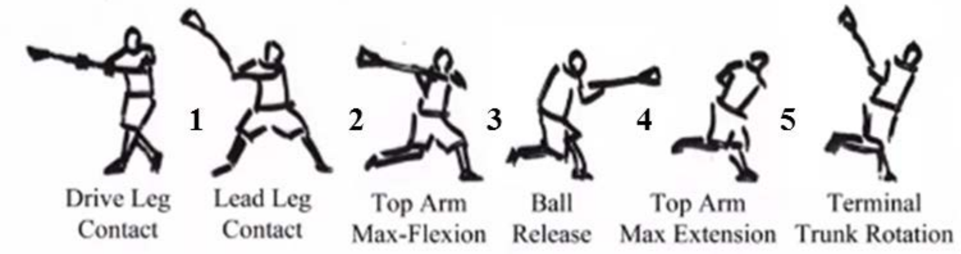


Figure 7. Foot orientation and target setup.

Participants were verbally instructed to shoot the ball at the randomly-assigned target as accurately as possible while attempting to accurately hit the target. A successful trial included the participant performing the overhand shot with their stride foot landing in the correct foot contact orientation on the force plate, per the instruction of the researcher. As accuracy was an outcome variable, the accuracy of the shot was not required to determine a successful trial. To combat the onset of fatigue, participants were given thirty seconds of rest between trials. To identify possible fatigue, the Borg rating of percieved exertion (RPE) scale (Appendix C) was administered to the participant before performing the baseline shots for maximal ball velocity and after each set of twelve shots for accuracy.



1 = Phase 1, 2 = Phase 2, 3 = Phase 3, 4 = Phase 4, 5 = Phase 5. Adapted from Mercer and Nielson (2013)[3]

Figure 8. Phases of the overhand lacrosse shot.

Kinematic and kinetic observation were divided into the five phases of the overhand lacrosse shot (Figure 8). These five phases were adapted from the six events of the shot: 1) approach, 2) crank back, 3) stick acceleration, 4) stick deceleration, 5) follow-through, and 6) recovery.[3] Due to sensor distortion in the beginning of each trial as a result of the participant being outside of the capture volume prior to the shot, the six events were restructured and only five phases were utilized, as some components of the recovery phase did not apply to the situation of the lab experiment. Phase 1 was between the first instance of drive (i.e., non-stride) foot contact and the first instance of stride foot contact onto the force plate. The instance of vertical ground reaction force recorded by the force plate was used to determine stride foot contact; however, with only one force plate, drive-leg foot contact was determined at the lowest linear velocity in the x-direction for the drive foot as calculated by the drive-foot sensor. Phase 2 was between stride foot contact to maximum elbow flexion of the top (dominant) arm. Phase 3 was between maximum elbow flexion of the top (dominant) arm to ball release. Because we were unable to track the ball and stick within the electromagnetic system, ball release was estimated. One researcher estimated ball release by observing ball release in high-speed video captured at 240 frames/second and synchronizing it with the skeletal animations for seventy-nine shots from nine participants measured at 240 Hz using Dartfish software (Dartfish 7, Fribourg, Switzerland). From this synchronization, it was determined that ball release from the lacrosse stick occurred, on average, 6.86 frames from maximal dominant hand velocity. Given that the sampling rate was set at 240 frames/second, it was determined that ball release occurred, on average, 0.029 seconds from the instant of maximal dominant hand velocity. Therefore, maximal dominant hand velocity was used for all participants to estimate ball release. Phase 4 was between ball release to maximum elbow extension of the top (dominant) arm. Last, Phase 5 was between maximum elbow extension of the top (dominant) arm to the end of trunk rotation (largest value of trunk rotation) in the transverse plane.

Experimental Design

Kinematic and kinetic data were averaged for each phase and target location across the three foot contact orientations. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) software (version 23.0; IBM Corp., Armonk, NY). The alpha level for all analyses was set *a priori* at $p \leq 0.05$. All data were exported using The MotionMonitor® and were compiled in Microsoft Excel to prepare for statistical analysis. To address the first research question, a 3 (Foot Orientation) x 8 (Segment) repeated mesaures analysis of variance (RM ANOVA) was used to determine differences in pelvis, trunk, and bilateral upper extremity angular velocities as a result of stride foot contact orientation. For the second research question, a RM ANOVA was used to determine differences in ball velocity as a result of stride foot contact orientation. To answer the third research question, a Pearson product-moment correlation was used to investigate a correlation between pelvis, trunk, and bilateral upper extremity angular velocities and ball velocity. The fourth research question was answered using a 3 (Foot Orientation) x 2 (Shot Velocity) RM ANOVA to determine a difference between mean ball velocity when shooting for accuracy and mean ball velocity when shooting at maximal effort. Last, the fifth research question was investigated using two RM ANOVA tests to determine differences in ankle and knee joint moments as a result of stride foot contact orientation.

CHAPTER IV

RESULTS

The purpose of this project was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, as well as joint moments of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting. Sixteen male lacrosse players were recruited to participate. One participant violated the inclusion criteria; therefore the participant’s data were not included for statistical analysis. As a result, only data from the remaining fifteen participants (16.60 ± 5.54 yrs.; 168.93 ± 16.14 cm; 63.05 ± 18.86 kg; 6.67 ± 3.39 yrs. experience) were used for statistical analysis. This chapter outlines and describes the results of the study and are arranged accordingly:

RQ1: Does stride foot contact orientation affect the average angular velocities of the pelvis, trunk, and bilateral upper extremities during the phases of the overhand lacrosse shot?

RQ2: Does stride foot contact orientation affect ball velocity?

RQ3: Is there a correlation between maximum angular velocities of the pelvis, trunk, and bilateral upper extremities and ball velocity during the phases of the overhand lacrosse shot?

RQ4: Is a speed-accuracy tradeoff present in the overhand lacrosse shot?

RQ5: How does stride foot contact orientation affect ankle and knee joint moments throughout the shooting motion?

Research Question 1. Does stride foot contact orientation affect the average angular velocities of the pelvis, trunk, and bilateral upper extremities during the phases of the overhand lacrosse shot?

Fifteen male lacrosse players (16.60 ± 5.54 yrs.; 168.93 ± 16.14 cm; 63.05 ± 18.86 kg; 6.67 ± 3.39 yrs. experience) volunteered to participate. Kinematic data were found to be normally distributed and did not violate the Shapiro-Wilk Test of normality. A Mauchly's W test was used to assess sphericity of the data. Due to a significant Mauchly's W, a Greenhouse-Geisser correction was utilized to reduce the inflation of the F-statistic for the segment variable. Means and standard errors of the resultant kinematic data are shown in Table 3. A 3 (Foot Orientation) x 8 (Segment) RM ANOVA revealed significant main effects for the foot orientation ($F_{2,28} = 6.63$, $p = 0.004$, $\eta^2 = 0.322$) and segment ($F_{2.672,98} = 104.71$, $p < 0.001$, $\eta^2 = 0.882$) variables; however, there was no significant interaction for the foot orientation and segment variables ($F_{3.589,196} = 0.783$, $p = 0.687$, $\eta^2 = 0.053$) (Appendix D). Main effects were assessed by comparing marginal means and standard errors for each segment variable across stride foot orientations presented in Table 4.

Table 3. Means and standard errors of resultant kinematic data.

Foot Orientation	**Segment**	**Mean (mph)**	**Std. Error**
Closed	Pelvis Angular Velocity	167.79	14.89
	Trunk Angular Velocity	269.53	10.25
	Non-Dominant Humerus Angular Velocity	419.93	25.09
	Non-Dominant Forearm Angular Velocity	462.71	19.40
	Non-Dominant Hand Angular Velocity	602.24	36.83
	Dominant Humerus Angular Velocity	451.43	25.43
	Dominant Forearm Angular Velocity	505.35	29.62
	Dominant Hand Angular Velocity	589.75	30.09
In-line	Pelvis Angular Velocity	147.78	15.70
	Trunk Angular Velocity	253.81	9.24
	Non-Dominant Humerus Angular Velocity	396.82	25.61
	Non-Dominant Forearm Angular Velocity	439.41	19.93
	Non-Dominant Hand Angular Velocity	575.25	38.78
	Dominant Humerus Angular Velocity	429.00	26.22
	Dominant Forearm Angular Velocity	481.83	32.31
	Dominant Hand Angular Velocity	564.00	33.89
Open	Pelvis Angular Velocity	143.65	15.81
	Trunk Angular Velocity	255.55	8.74
	Non-Dominant Humerus Angular Velocity	397.76	24.27
	Non-Dominant Forearm Angular Velocity	434.16	19.63
	Non-Dominant Hand Angular Velocity	575.82	37.63
	Dominant Humerus Angular Velocity	431.43	26.36
	Dominant Forearm Angular Velocity	482.83	32.19
	Dominant Hand Angular Velocity	565.27	34.61

Table 4. Mean differences of raw kinematic data across stride foot orientations.

Segment	(I) Foot Orientation	(J) Foot Orientation	Mean Differences (I-J)	Std. Error	*p*
Pelvis Angular Velocity	Closed	In-line	20.01*	3.68	0.000
		Open	24.15*	4.89	0.000
	In-line	Closed	-20.01*	3.68	0.000
		Open	4.13	2.50	0.121
	Open	Closed	-24.15*	4.89	0.000
		In-line	-4.13	2.50	0.121
Trunk Angular Velocity	Closed	In-line	15.72*	3.81	0.001
		Open	13.98*	5.54	0.024
	In-line	Closed	-15.72*	3.81	0.001
		Open	-1.74	3.94	0.665
	Open	Closed	-13.98*	5.54	0.024
		In-line	1.74	3.94	0.665
Non-Dominant Humerus Angular Velocity	Closed	In-line	23.10*	6.77	0.004
		Open	22.16*	9.44	0.034
	In-line	Closed	-23.10*	6.77	0.004
		Open	-0.94	6.34	0.884
	Open	Closed	-22.16*	9.44	0.034
		In-line	0.94	6.34	0.884
Non-Dominant Forearm Angular Velocity	Closed	In-line	23.30*	6.08	0.002
		Open	28.55*	9.36	0.009
	In-line	Closed	-23.30*	6.08	0.002
		Open	5.25	6.20	0.412
	Open	Closed	-28.55*	9.36	0.009
		In-line	-5.25	6.20	0.412
Non-Dominant Hand Angular Velocity	Closed	In-line	26.99*	10.86	0.026
		Open	26.42*	10.83	0.029
	In-line	Closed	-26.99*	10.86	0.026
		Open	-0.57	6.51	0.932
	Open	Closed	-26.42*	10.83	0.029
		In-line	0.57	6.51	0.932
Dominant Humerus Angular Velocity	Closed	In-line	22.43*	9.65	0.036
		Open	19.99	10.26	0.072
	In-line	Closed	-22.43*	9.65	0.036
		Open	-2.44	6.36	0.707
	Open	Closed	-19.99	10.26	0.072
		In-line	2.44	6.36	0.707
Dominant Forearm Angular Velocity	Closed	In-line	23.51*	10.79	0.047
		Open	22.52	10.70	0.054
	In-line	Closed	-23.51*	10.79	0.047
		Open	-0.99	7.35	0.894
	Open	Closed	-22.52	10.70	0.054
		In-line	0.99	7.35	0.894
Dominant Hand Angular Velocity	Closed	In-line	25.74*	11.39	0.040
		Open	24.48	12.44	0.069
	In-line	Closed	-25.74*	11.39	0.040
		Open	-1.26	8.33	0.882
	Open	Closed	-24.48	12.44	0.06
		In-line	1.26	8.33	0.882

* - significance at $p \leq 0.05$.

Research Question 2. Does stride foot contact orientation affect ball velocity?

Maximal ball velocity data were found to be normally distributed and did not violate the Shapiro-Wilk Test of normality. Due to a non-significant Mauchly's W, sphericity was assumed. Means and standard errors for ball velocity are shown in Table 5. A RM ANOVA revealed a significant main effect of foot orientation ($F_{2,28} = 9.83$, $p = 0.001$, $\eta^2 = 0.412$) (Appendix D). Main effects were assessed by comparing marginal means and standard errors for ball velocity across stride foot orientations presented in Table 6.

Table 5. Means and standard errors for maximal ball velocity across stride foot orientations.

Foot Orientation	**Mean (mph)**	**Std. Error**
Closed	63.13	4.04
In-line	61.67	4.33
Open	60.33	4.09

Table 6. Mean differences of ball velocity across stride foot orientations.

(I) Foot Orientation	**(J) Foot Orientation**	**Mean Differences (I-J)**	**Std. Error**	***p***
Closed	In-line	1.47*	0.65	0.042
	Open	2.80*	0.62	<0.001
In-line	Closed	-1.47*	0.65	0.042
	Open	1.33*	0.62	0.050
Open	Closed	-2.80*	0.62	<0.001
	In-line	-1.33*	0.62	0.050

* - significance at $p \leq 0.05$.

Research Question 3. Is there a correlation between maximum angular velocities of the pelvis, trunk, and bilateral upper extremities and ball velocity during the phases of the overhand lacrosse shot?

Maximum angular velocity data for the pelvis, trunk, and upper extremities, averaged across stride foot contact orientation, were found to be normally distributed and did not violate the Shapiro-Wilk Test of normality. Means and standard errors for the maximal angular velocities of the pelvis, trunk, and upper extremities are shown in Table 7. Significant Pearson correlation coefficients were found for ball velocity and all kinematic angular velocity variables, with the exception of non-dominant hand angular velocity: pelvis angular velocity (r = 0.551, $p = 0.033$), trunk angular velocity (r = 0.743, $p = 0.001$), non-dominant humerus angular velocity (r = 0.865, $p < 0.001$), non-dominant forearm angular velocity (r = 0.812, $p < 0.001$), non-dominant hand angular velocity (r = 0.438, $p = 0.102$), dominant humerus angular velocity (r = 0.640, $p = 0.010$), dominant forearm angular velocity (r = 0.519, $p = 0.048$), and dominant hand angular velocity (r = 0.779, $p = 0.001$) (Appendix D).

Table 7. Means and standard errors for maximal angular velocities of the pelvis, trunk, upper extremities, and ball velocity.

Kinematic Variables	**Mean**	**Std. Error**	**r**	***p***
Pelvis Angular Velocity (˚/s)	533.17	29.40	0.551*	0.033
Trunk Angular Velocity (˚/s)	799.97	33.35	0.743*	0.001
Non-Dominant Humerus Angular Velocity (˚/s)	977.28	42.46	0.865*	<0.001
Non-Dominant Forearm Angular Velocity (˚/s)	1002.20	43.52	0.812*	<0.001
Non-Dominant Hand Angular Velocity (˚/s)	1422.05	79.46	0.438	0.102
Dominant Humerus Angular Velocity (˚/s)	1112.34	68.74	0.640*	0.010
Dominant Forearm Angular Velocity (˚/s)	1291.99	79.86	0.519*	0.048
Dominant Hand Angular Velocity (˚/s)	1644.02	75.23	0.779*	0.001

* - significance at $p \leq 0.05$.

Research Question 4. Is a speed-accuracy tradeoff present in the overhand lacrosse shot?

Ball velocity data were found to be normally distributed and did not violate the Shapiro-Wilk Test of normality. Due to a significant Mauchly's W, a Greenhouse-Geisser correction was utilized to reduce the inflation of the F-statistic for the foot orientation data. Due to a non-significant Mauchly's W, sphericity was assumed for the shot velocity data. Means and standard errors for maximal and accuracy velocities are presented in Table 8. Means and standard errors for ball velocities across stride foot orientations are presented in Table 9. A 3 (Foot Orientation) x 2 (Shot Velocity) RM ANOVA revealed a significant main effect of foot orientation ($F_{1.366,28} = 7.15$, $p = 0.009$, $\eta^2 = 0.338$) and shot velocity ($F_{1,14} = 27.83$, $p < .0.001$, $\eta^2 = 0.665$); however, there was no significant interaction of the foot orientation and shot velocity variables ($F_{2,28} = 1.38$, $p = 0.270$, $\eta^2 = 0.089$) (Appendix D). Main effects were assessed by comparing marginal means and standard errors for ball velocity when shooting for accuracy and at maximal effort presented in Table 10. Main effects were assessed by comparing marginal means and standard errors for ball velocity across stride foot orientations presented in Table 11.

Table 8. Means and standard errors for maximal and accuracy shot velocities.

Shot Velocity	**Mean (mph)**	**Std. Error**
Accuracy Velocity	53.89	3.17
Maximal Velocity	61.71	4.14

Table 9. Means and standard errors for shot velocity across stride foot orientations.

Foot Orientation	**Mean (mph)**	**Std. Error**
Closed	59.26	3.43
In-line	57.60	3.41
Open	56.81	3.36

Table 10. Mean differences of ball velocity when shooting for accuracy and at maximal effort.

(I) Shot Velocity	**(J) Shot Velocity**	**Mean Difference (I-J)**	**Std. Error**	***p***
Accuracy Velocity	Maximal Velocity	-7.82*	1.48	0.000

* - significance at $p \leq 0.05$.

Table 11. Mean differences of ball velocity across stride foot orientations.

(I) Foot Orientation	**(J) Foot Orientation**	**Mean Difference (I-J)**	**Std. Error**	***p***
Closed	In-line	1.66*	0.62	0.017
	Open	2.45*	0.73	0.004
In-line	Closed	-1.66*	0.62	0.017
	Open	0.79*	0.35	0.037
Open	Closed	-2.45*	0.73	0.004
	In-line	-0.79*	0.35	0.037

* - significance at $p \leq 0.05$.

Research Question 5. How does stride foot contact orientation affect ankle and knee joint moments throughout the shooting motion?

Ankle and knee mass-normalized moment data were found to be normally distributed and did not violate the Shapiro-Wilk Test of normality. For the first RM ANOVA test, sphericity was assumed for the ankle kinetic data due to a non-significant Mauchly's W. Means and standard errors for ankle moments across stride foot contact orientations are presented in Table 12. For the second RM ANOVA test, a Greenhouse-Geisser correction was used for the knee kinetic data due to a significant Mauchly's W. Means and standard errors for knee moments across stride foot orientations are presented in Table 13. The first RM ANOVA revealed no significant main effect of foot orientation on ankle moments ($F_{2,28} = 3.18$, $p = 0.057$, $\eta^2 = 0.185$) (Appendix D). Main effects were assessed by comparing ankle moment means and standard errors across stride foot orientations presented in Table 14. The second RM ANOVA revealed a significant main effect of foot orientation on knee moments ($F_{1.36,28} = 4.03$, $p = 0.048$, $\eta^2 = 0.223$) (Appendix D). Main effects were assessed by comparing knee moment means and standard errors across stride foot orientations presented in Table 15.

Table 12. Means and standard errors for ankle moments across stride foot orientations.

Foot Orientation	**Mean (Nm/kg)**	**Std. Error**
Closed	0.29	0.08
In-line	0.34	0.07
Open	0.44	0.07

Table 13. Means and standard errors for knee moments across stride foot orientations.

Foot Orientation	**Mean (Nm/kg)**	**Std. Error**
Closed	-0.37	0.04
In-line	-0.36	0.03
Open	-0.26	0.04

Table 14. Mean differences in ankle moments across stride foot orientations.

(I) Foot Orientation	**(J) Foot Orientation**	**Mean Difference (I-J)**	**Std. Error**	***p***
Closed	In-line	-0.05	0.06	0.424
	Open	-1.43	0.07	0.051
In-line	Closed	0.05	0.06	0.424
	Open	-0.09*	0.04	0.035
Open	Closed	0.143	0.07	0.051
	In-line	0.09*	0.04	0.035

Table 15. Mean differences in knee moments across stride foot orientations.

(I) Foot Orientation	**(J) Foot Orientation**	**Mean Difference (I-J)**	**Std. Error**	***p***
Closed	In-line	-0.01	0.03	0.776
	Open	-0.11	0.06	0.067
In-line	Closed	0.01	0.03	0.776
	Open	-0.10*	0.04	0.021
Open	Closed	0.11	0.06	0.067
	In-line	0.10*	0.04	0.021

* - significance at $p \leq 0.05$.

CHAPTER V

DISCUSSION

The purpose of this study was to examine the effect of stride foot contact orientation on the angular kinematics of the pelvis, trunk, and bilateral upper extremities, as well as joint moments of the ankle and knee, maximal ball velocity, and accuracy performance in male lacrosse players during overhand shooting. This chapter discusses the results from each research question, as well as elaborates on the application of the findings to male lacrosse players of all ages and skill levels.

Does stride foot contact orientation affect the average angular velocities of the pelvis, trunk, and bilateral upper extremities during the phases of the overhand lacrosse shot?

The aim was to investigate the effect of three stride foot contact orientations (closed, in-line, and open) on angular velocities of the pelvis, trunk, and upper extremities during the phases of the overhand lacrosse shot. It was hypothesized that utilizing an in-line stride foot orientation when performing the overhand lacrosse shot would result in greater angular velocities compared to closed and open stride foot orientations. Results from this study revealed that utilizing a closed foot orientation during overhand shooting elicited greater angular velocities for the pelvis, trunk, and upper extremity segments when compared to in-line and open foot orientations. Additionally, it was observed that there were no significant differences in angular velocities of the pelvis, trunk, and upper extremities when comparing the in-line and open stride foot orientations (Figure 9).

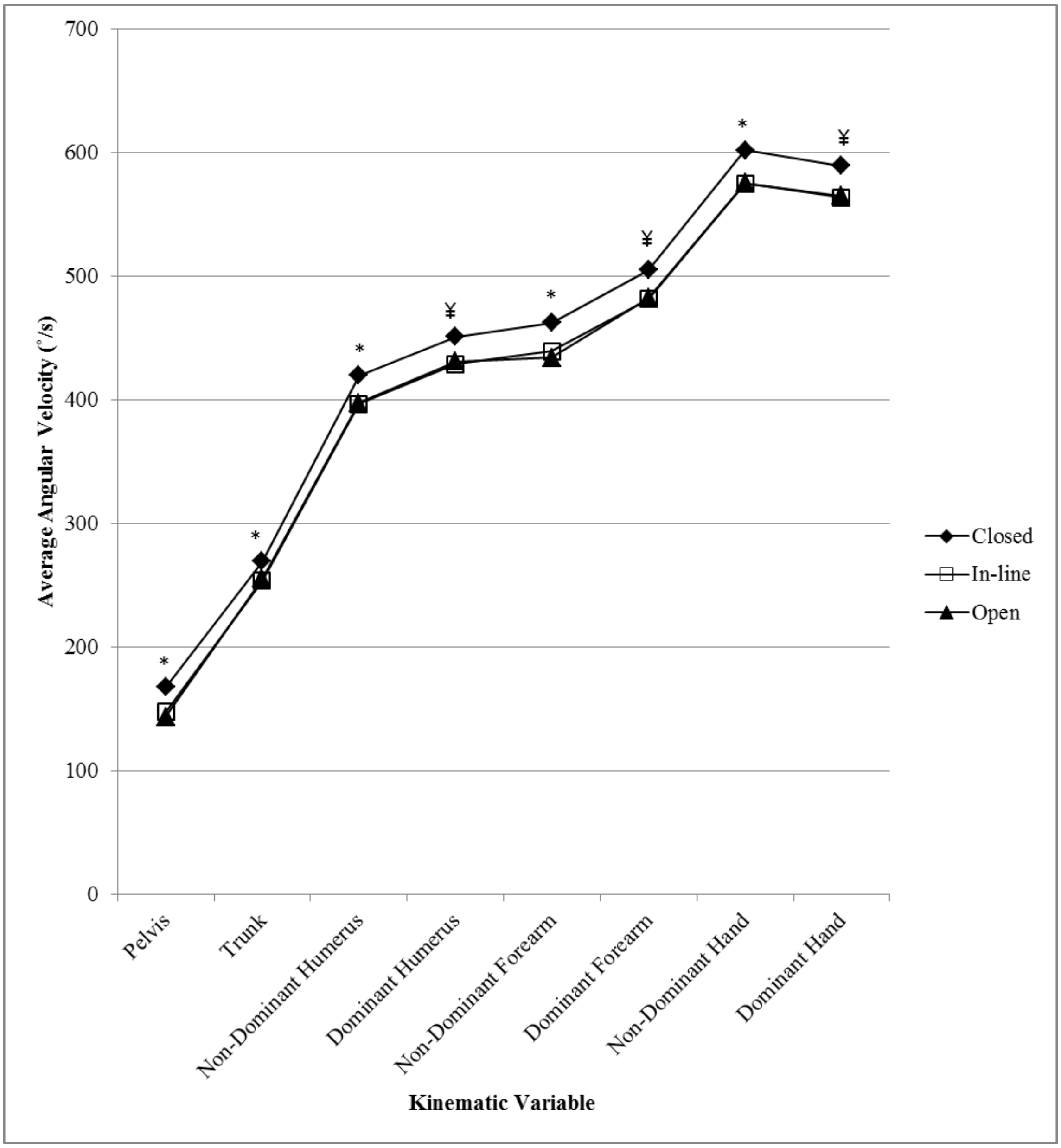


Figure 9. Angular velocities of the pelvis, trunk , and upper extremity as a function of foot orientation.

* - Angular velocities of the pelvis, trunk, and upper extremities are significantly greater in the closed foot orientation compared to the in-line and open foot orientations ($p \leq 0.05$).

¥ - Angular velocities of the pelvis, trunk, and upper extremities are significantly greater in the closed foot orientation compared to the in-line foot orientation, but not the open foot orientation ($p \leq 0.05$).

These findings contradict the null hypothesis that an in-line foot orientation would maximize angular velocities of these segments. These results are interesting given that previous research investigating the effect of foot orientation in overhead throwing tasks, such as baseball throwing, has found that utilizing an in-line stride foot orientation in baseball pitching maximizes performance.[15-17,91] Additionally, previous research suggests that closed and open orientations of the stride foot are detrimental to kinetic chain function, force generation, and energy transfer in baseball pitching.[15-17,91] Specifically, a closed foot orientation is believed to decrease pelvis and trunk rotation range of motion resulting in decreased force generation in the kinetic chain.[16] Likewise, an open foot orientation has been shown to result in premature pelvis rotation, thereby uncoupling the kinetic chain and increasing the force that must be generated at the shoulder to maintain ball velocity.[16,91]

Interestingly, fourteen of the fifteen participants were observed to preferentially utilize a closed foot orientation to perform the overhand shot during the warm-up. As a result, angular velocities of the pelvis, trunk, and upper extremities may have been greater in this sample when landing in a closed orientation as a result of familiarity and kinesthetic awareness associated with the closed foot orientation. Another potential explanation for the increased angular velocities when utilizing a closed stride foot orientation could involve the stretch-shortening cycle. In regards to baseball pitching, one study suggested that tissues placed on a stretch contract more rapidly and efficiently.[92] In lacrosse, landing in a closed orientation during the overhand shot may be advantageous for the player to position their non-dominant arm over their dominant shoulder and place a stretch on the non-dominant latissimus dorsi and other trunk rotators. It may be possible that when a lacrosse player lands in a closed foot orientation, they are able to provide a more stable anchor for the non-dominant latissimus dorsi and other trunk rotators to produce a more forceful concentric contraction. Again, in baseball pitching, placing a muscle on a stretch increases the muscles' ability to contract and maximize energy transfer from the pelvis to the upper extremity via the kinetic chain resulting in greater angular velocities of the upper extremities.[92]

Additionally, Figure 9 also illustrates evidence of the summation of speed principle occuring in the overhand lacrosse shot. This is evidenced by the angular velocity of the pelvis being the smallest, followed by the trunk, the bilateral humeruses, bilateral forearms, and lastly and most distally, bilateral hands.[46] The summation of speed principle has been noted in overhead throwing and striking tasks, such as baseball throwing[17,60-64] and the tennis serve,[20,28,65-67] as well as stick sports that require trunk rotation to perform a task, such as golf[32] and hockey.[26,30] As a result, it seems likely that the summation of speed principle would also apply to lacrosse shooting. Contrary to research that has found an in-line foot orientation to maximize the summation of segmental speeds,[15-17,91] the current study revealed that a closed foot orientation maximizes the summation of segmental speeds in the overhand lacrosse shot compared to in-line and open foot orientations.

Figure 9 may also provide insight into the biomechanical nature of the overhand lacrosse shot, specifically determining if it is predominantly a "pulling" motion performed by the non-dominant limb, a "pushing" motion performed by the dominant limb, or both due to rotational force coupling. From Figure 9, a higher angular velocity of the dominant humerus and forearm compared to the non-dominant humerus and forearm in conjunction with a higher angular velocity of the non-dominant hand compared to the dominant hand may suggest the shooting motion is a combination of the two motions. Specifically, Figure 9 suggests that the dominant humerus and forearm are initally responsible for the resultant angular velocity of the lacrosse stick and ball. If the average velocities of the segments reflected the velocities of the segments at ball release, the non-dominant hand may be responsible for increasing the high-velocity movement of the stick and ball at the instance of ball release in the overhand shot. If true, this would suggest that a force couple occurs at one net axis of rotation formed by the dominant and non-dominant hands. Thus, this may possibly be a mechanical advantage in overhand lacrosse shooting to maximize the velocity of the ball as it exits the stick. As this finding is outside the scope of the current study, further research investigating timing within the shooting phases, as well as the use of surface electromyography to identify muscle contribution during the overhand shot is warranted to more accurately determine the true nature of the overhand lacrosse shot.

Research Question 2. Does stride foot contact orientation affect ball velocity?

The aim was to investigate the effect of stride foot orientation on ball velocity during the overhand lacrosse shot. Similar to findings that support utilizing an in-line stride foot orientation in baseball pitching to maximize ball velocity,[15-17,91] it was hypothesized that utilizing an in-line stride foot orientation when performing the overhand lacrosse shot would result in a greater ball velocity than closed and open stride foot orientations. Results revealed significant differences in ball velocity as a function of foot orientation. Specifically, it was observed that the closed stride foot orientation produced the greatest ball velocity, an in-line stride foot orientation produced a slightly slower ball velocity, and an open stride foot orientation produced the slowest ball velocity (Figure 10). Previous research investigating the effect of foot orientation in overhead throwing tasks, such as baseball throwing, suggests that stride foot orientation is related to ball velocity.[17,93,94] Specifically, a closed foot orientation is believed to decrease pelvis and trunk rotation range of motion resulting in decreased force generation in the kinetic chain and leading to a decrease in ball velocity.[16] Similarly, an open foot orientation has been shown to result in premature pelvis rotation, thereby uncoupling the kinetic chain and increasing the force that must be generated at the shoulder to maintain ball velocity. Thus, it is concluded that this disconnect in efficient energy transfer is believed to decrease velocity.[16,91]

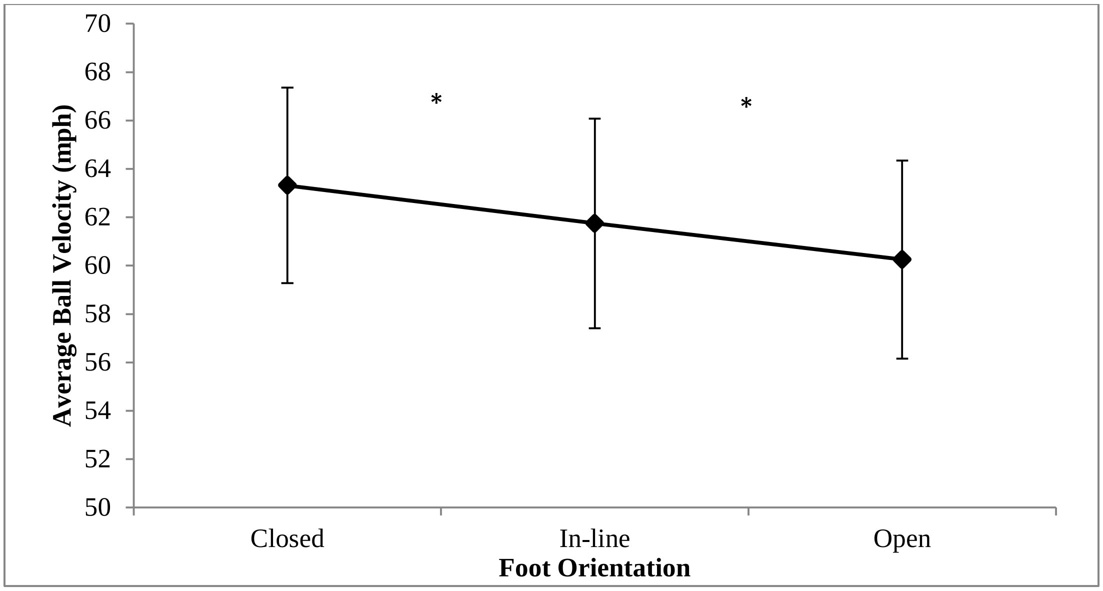


Figure 10. Average ball velocity as a function of stride foot orientation.
* - Ball velocity is significantly different across stride foot orientations ($p \leq 0.05$).

Again, fourteen of the fifteen participants were observed to preferentially utilize a closed foot orientation to perform the overhand shot during the warm-up. Due to preference for a closed stride foot orientation, ball velocity may be greater when landing in a closed orientation as a result of familiarity and kinesthetic awareness associated with the closed foot orientation. Another potential explanation for the increased ball velocity when utilizing a closed stride foot orientation, again, could involve the stretch-shortening cycle. In regards to baseball pitching, one study suggested that tissues placed on a stretch contract more rapidly and efficiently.[92] In lacrosse, landing in a closed orientation during the overhand shot may be advantageous for the player to position their non-dominant arm over their dominant shoulder and place a stretch on the non-dominant latissimus dorsi and other trunk rotators. It may be possible that when a lacrosse player lands in a closed foot orientation, they are able to provide a more stable anchor for the non-dominant latissimus dorsi and other trunk rotators to produce a more forceful concentric contraction. Again, in baseball pitching, placing a muscle on a stretch increases the muscles' ability to contract and maximize energy transfer from the pelvis to the upper extremity via the kinetic chain resulting in greater ball velocity.[92] These findings could provide a rationale for previous research that found foot orientation is strongly related to ball velocity in the baseball pitch.[15-17,91] The potential relationship between angular velocities of the pelvis, trunk, and upper extremities and ball velocity is investigated in the next section.

Research Question 3. Is there a correlation between maximum angular velocities of the pelvis, trunk, and bilateral upper extremities and ball velocity during the phases of the overhand lacrosse shot?

The aim was to investigate the potential relationship between the angular velocities of the pelvis, trunk, and upper extremities and ball velocity. Based on previous findings of overhead throwing and stick sports, it was hypothesized that angular velocities of the pelvis, trunk, and upper extremities would be strongly correlated with ball velocity. Results revealed that the angular velocities of the pelvis, trunk, and upper extremities are strongly correlated with ball velocity, with the exception of the non-dominant hand angular velocity (Figures 11-18). Previous research investigating the mechanics of the overhead throw, volleyball spike, and tennis serve has found a positive relationship between angular velocities of the trunk and upper extremities and ball velocity.[15-23,93,95-98] These findings are in agreement with stick sports, such as golf and hockey, which have also found a positive relationship between angular velocities of the trunk and upper extremities and projectile velocity.[24-27]

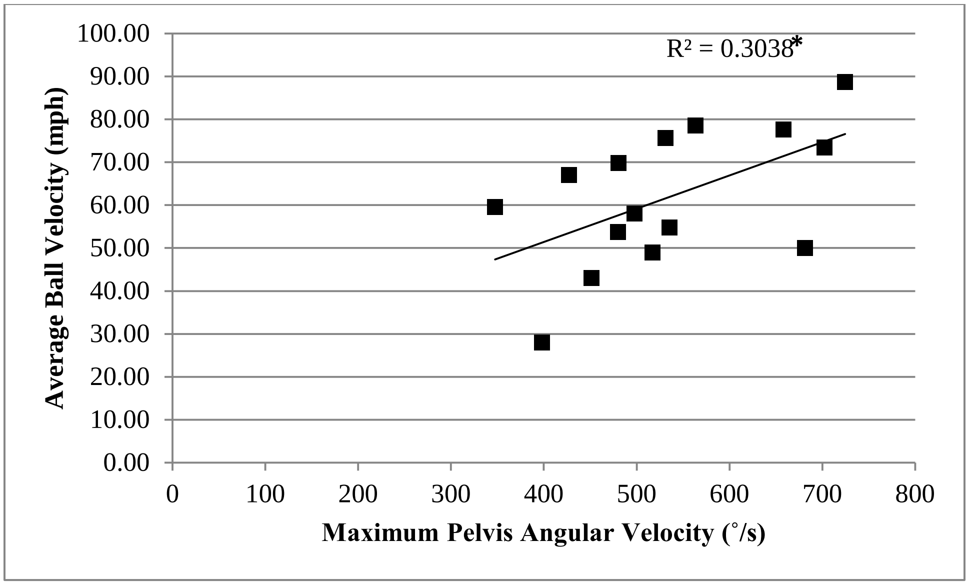


Figure 11. Relationship between maximum pelvis angular velocity and average ball velocity.
* - significance at $p \leq 0.05$.

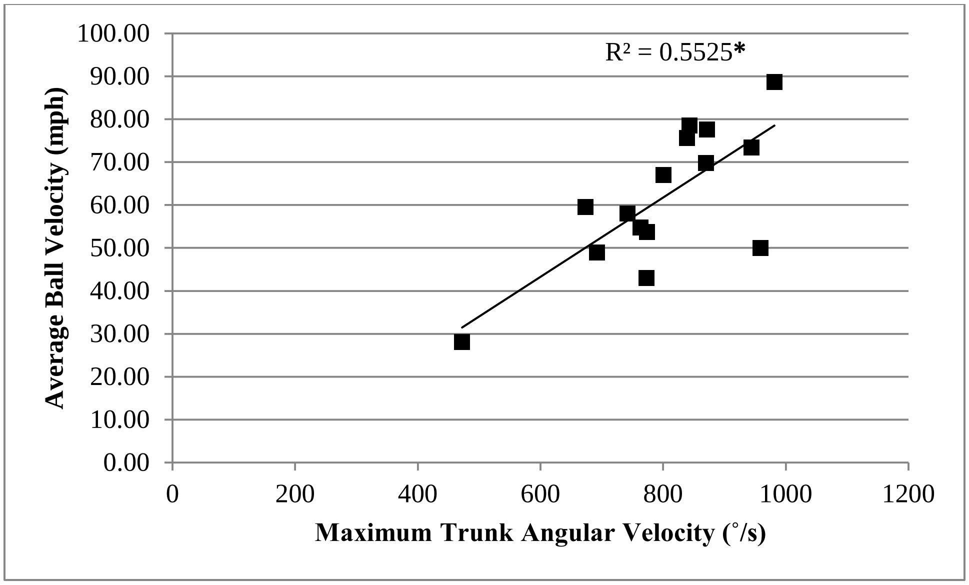


Figure 12. Relationship between maximum trunk angular velocity and average ball velocity.
* - significance at $p \leq 0.05$.

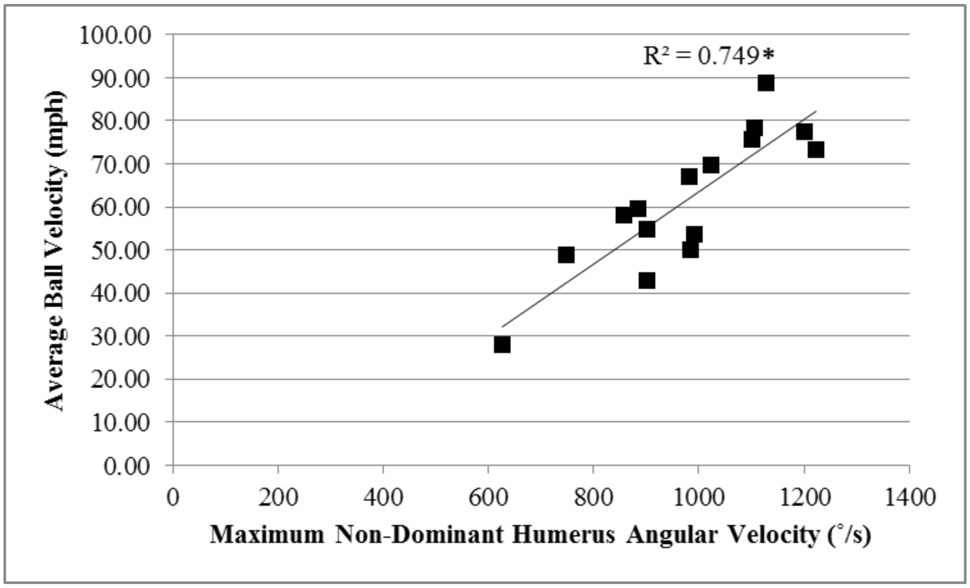


Figure 13. Relationship between maximum non-dominant humerus angluar velocity and average ball velocity. * - significance at $p \leq 0.05$.

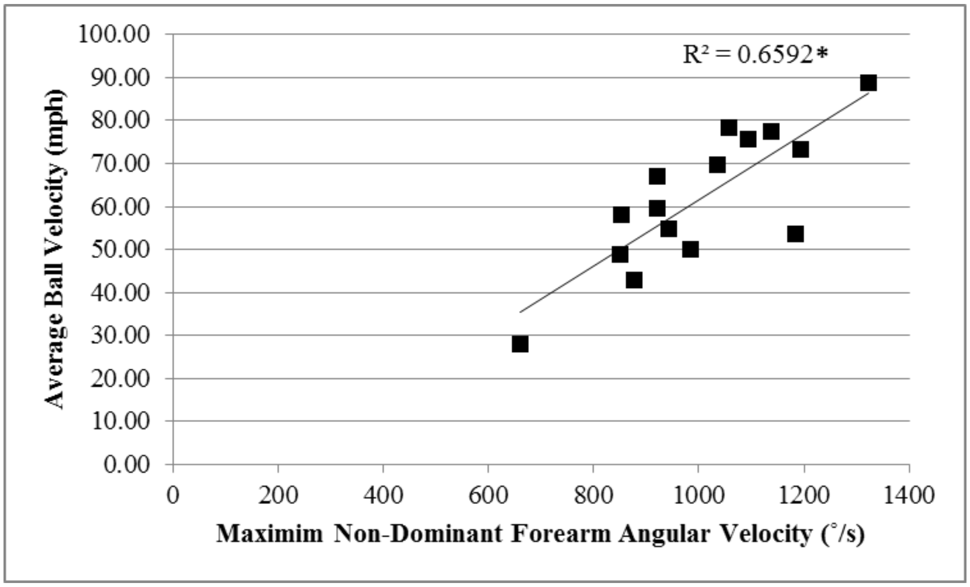


Figure 14. Relationship between maximum non-dominant forearm angular velocity and average ball velocity. * - significance at $p \leq 0.05$.

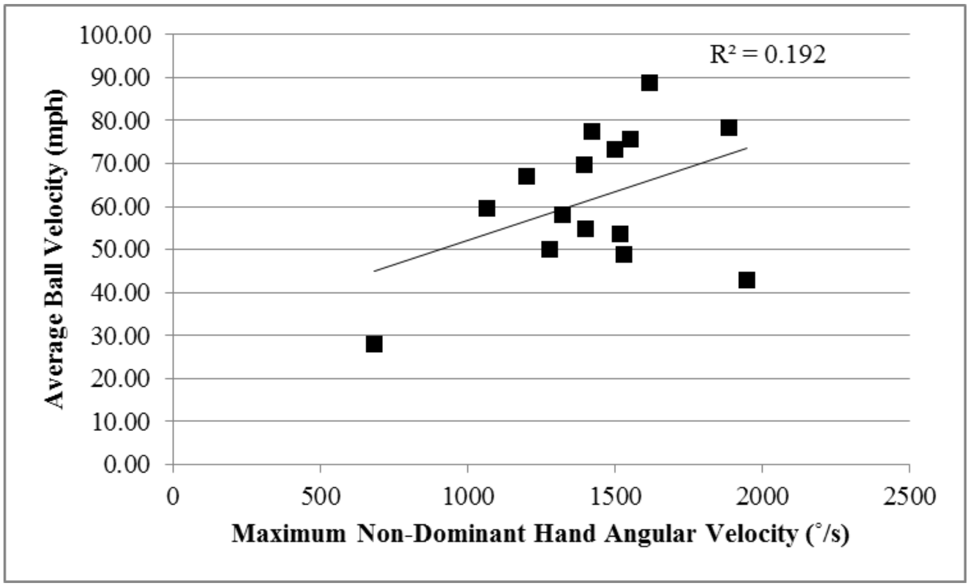


Figure 15. Relationship between maximum non-dominant hand angular velocity and average ball velocity.

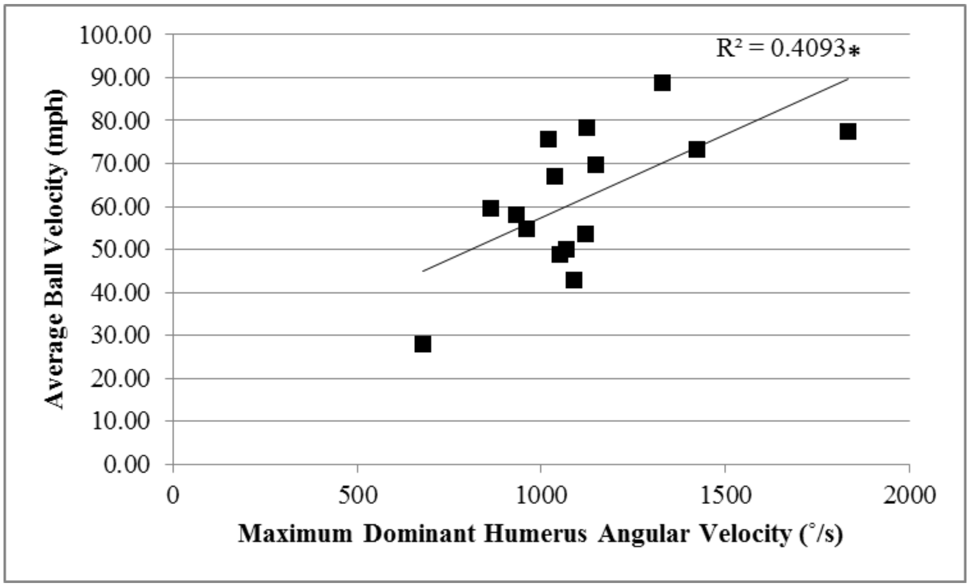


Figure 16. Relationship between maximum dominant humerus angular velocity and average ball velocity. * - significance at *p* ≤ 0.05.

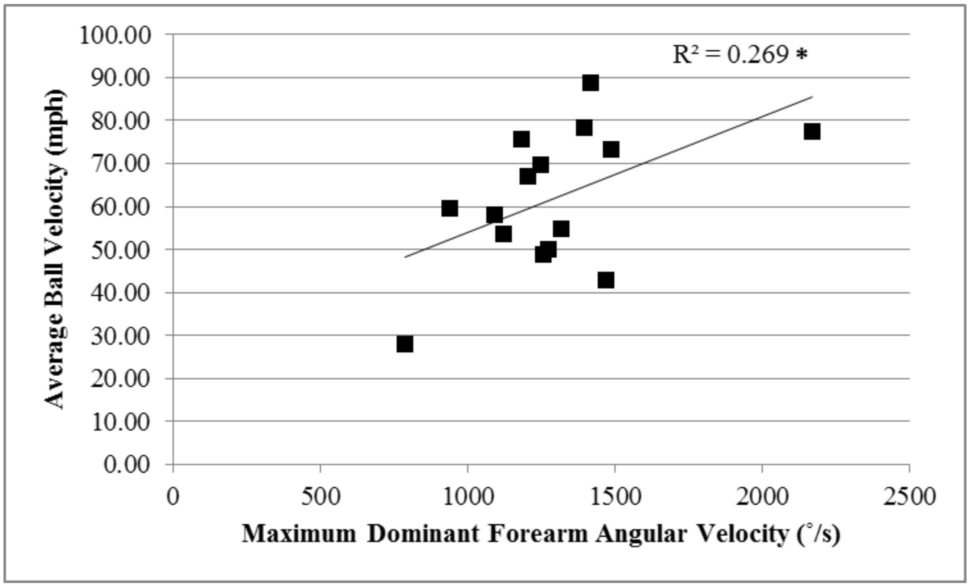


Figure 17. Relationship between maximum dominant forearm angular velocity and average ball velocity. * - significance at *p* ≤ 0.05.

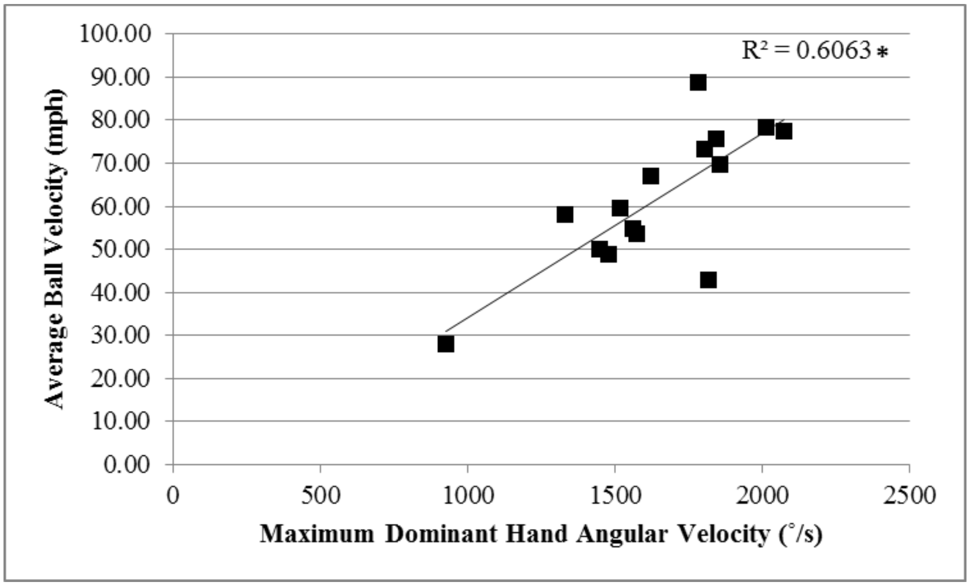


Figure 18. Relationship between maximum dominant hand angular velocity and average ball velocity. * - significance at $p \leq 0.05$.

Research Question 4. Is a speed-accuracy tradeoff present in the overhand lacrosse shot?

The aim was to investigate the presence of a speed-accuracy tradeoff, such that as shot speed increases; accuracy decreases, and vice versa. It was hypothesized that overhand lacrosse shooting would be affected by a speed-accuracy tradeoff. Results of this study revealed a significant speed-accuracy tradeoff occurs when performing the overhand lacrosse shot (Figure 19). These findings agree with previous research that has found the presence of a speed-accuracy tradeoff in baseball and cricket,[36,37,39] handball,[40-42] water polo,[43] tennis,[28] golf,[31] and hockey.[25-27] Participants shot the ball at an average velocity of 53.89 mph when shooting for accuracy; however, the same participants shot the ball at an average velocity of 61.71 mph when shooting with maximal effort, resulting in a significant mean difference of 7.82 mph, with participants shooting at 87.33% of maximal velocity when shooting for accuracy. While slightly higher than typically reported values, these findings agree with previous research that has found accuracy is maximized when the velocity of a projectile it between 70-92% of its maximal velocity.[35-39,42,43] However, there may be developmental factors that influence a tradeoff for speed and accuracy. For example, previous research has found that a speed-accuracy tradeoff only appears to affect individuals inexperienced with the task they are performing.[22,29,31,41,42,52] The current study investigated a speed-accuracy tradeoff within experienced youth and collegiate male lacrosse players (16.60 ± 5.54 yrs.; 168.93 ± 16.14 cm; 63.05 ± 18.86 kg; 6.67 ± 3.39 yrs. experience); therefore, future research should investigate a speed-accuracy tradeoff between participants of varying ages and years of playing experience. Such research is important to examine speed and accuracy differences associated with developmental effects to improve performance outcomes in all groups and skill levels.

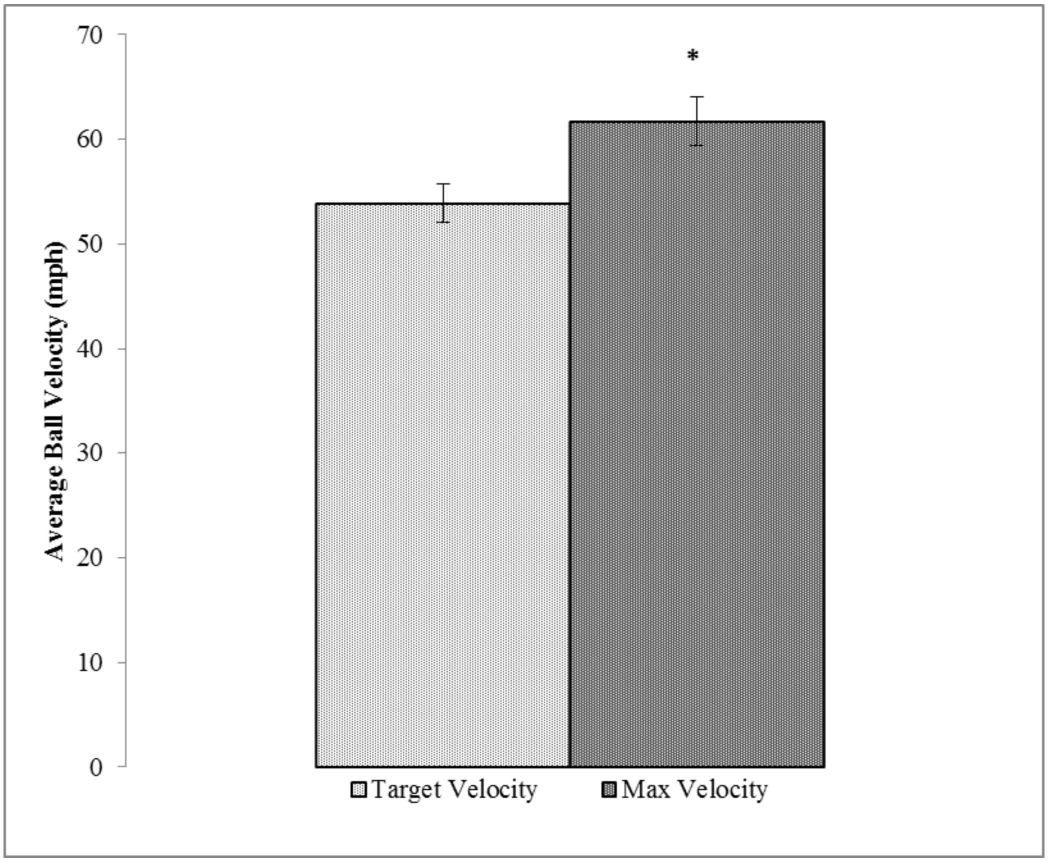


Figure 19. Shot velocities when shooting for accuracy and when shooting at maximal velocity. * - significance at $p \leq 0.05$.

Research Question 5. How does stride foot contact orientation affect ankle and knee joint moments throughout the shooting motion?

The aim was to investigate differences in ankle and knee kinetics as a result of stride foot contact orientation. It was hypothesized that stride leg ankle and knee joint moments in the transverse plane would be greater in the closed stride foot orientation compared to the in-line and open stride foot orientations. The current study revealed no significant differences in ankle moments as a function of foot orientation (Figure 20); however, significant differences were revealed in knee moments as a function of foot orientations (Figure 21).

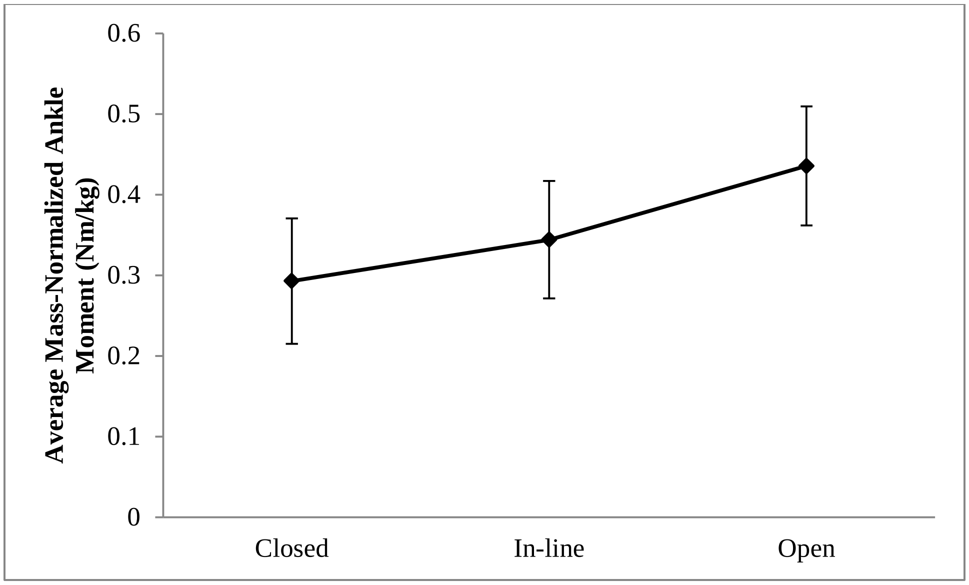


Figure 20. Mass-normalized ankle moments across stride foot orientations.
(+) - Counterclockwise rotation.

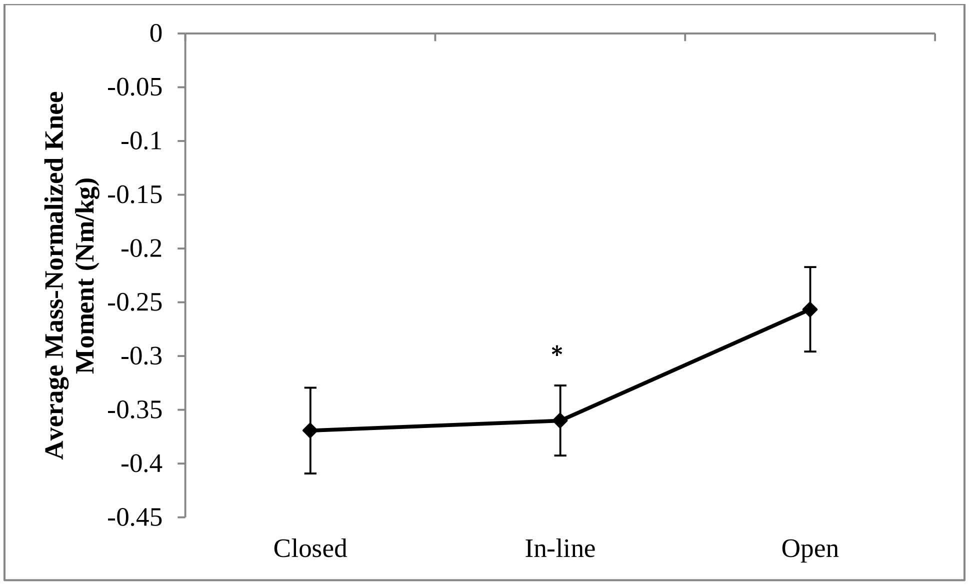


Figure 21. Mass-normalized knee moments across stride foot orientations.
(-) - Clockwise rotation. * - The knee moment in the in-line stride foot orientation is significantly greater than the knee moment in the open stride foot orientation ($p \leq 0.05$).

While it was not statistically significant, the trend of the data suggests that the ankle of the stride leg experienced greater counterclockwise (+) joint moments in the open foot orientation compared to the closed and in-line stride foot orientations.

Conversely, it was revealed that the knee of the stride leg experienced significantly greater clockwise (-) joint moments in the in-line stride foot orientation compared to the open stride foot orientation; however, there were no differences in the closed stride foot orientation and the in-line and open stride foot orientations. Subjecting the ankle and knee joints to these increased moments during a dynamic task, like the overhand lacrosse shot, may provide insight as to why the ankle and knee are commonly injured joints in lacrosse, especially in non-contact scenarios.[8-14]

In this study, ankle and knee joint moments were normalized to the participants' mass; therefore, further research should be conducted to determine if the average ankle and knee moments experienced in this study yielded values near injury thresholds. As this study was performed in a controlled laboratory setting with participants wearing tennis shoes, future research should investigate joint moments of the ankle and knee as a result of stride foot orientation and the interface between cleats and the playing surface, which would be more realistic to a competitive lacrosse scenario. These findings would assist coaches and players to determine the safest stride foot orientation to use to minimize joint moments during overhand shooting.

Conclusions

The results of the current study revealed several critical components of the biomechanics associated with overhand lacrosse shooting in youth and collegiate male lacrosse players. These components may have significant implications for the coaching and training of male lacrosse players of all ages and skill levels. Results from this study indicate that stressing the importance of proper stride foot orientation when initiating an overhand shot may be beneficial for training male lacrosse players to shoot with greater velocity. Specifically, these findings suggest that instructing a player to land in a closed stride foot orientation maximizes the angular velocities of their pelvis, trunk, and upper extremities and may produce a higher velocity shot than when utilizing an in-line or open stride foot orientation. However, these results suggest while placing the stride foot in a closed or in-line orientation may increase shot velocity, the knee of the stride leg is subject to an increased internal rotation joint moment. Conversely, placing the stride foot in an open orientation not only decreases shot velocity, but may also subject the ankle to an increased external rotation joint moment. Lastly, this study suggests that players should attempt to decrease their shot speed when prioritizing accuracy. Consistent with the presence of a speed-accuracy tradeoff in similar overhead throwing, striking, and stick sports, accuracy is maximized when shot velocity is decreased, and vice versa. This concept may prove crucial in game-time scenarios in which scoring a goal is imperative to determine the outcome of a lacrosse game.

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Appendix A

Health and Sports History Questionnaire

Part 1. Participant Information

[Please print]

Name: ____

Age: _______ State: ________ Phone: ________________ Email: _____________________

Height: _____ft. _____in Weight: ________lbs.

Part 2. Athletic Participation

(Circle or fill in your responses)

1. Are you currently cleared to participate in lacrosse? **YES** **NO**

2. What is your dominant shooting arm? **RIGHT** **LEFT**

3. What position is your primary position? **ATTACK** **MIDFIELD**

4. At what age did you begin playing competitive lacrosse? __________

5. At what competition level are you currently playing? [Please circle]

Professional **NCAA Div. I** **NCAA Div. II** **NCAA Div. III** **Junior College** **High School**

Junior High **Youth League** **Other ______________________**

6. For how many years have you been participating at this level? ________

7. Do you play in every game? **YES** **NO**

8. Is lacrosse your primary sport? **YES** **NO**

List all sports you play competitively

____

9. During the season, how many hours per week do you spend performing the following?

a. Playing lacrosse: _____**hrs./week**

b. Upper extremity training/conditioning: _____**hrs./week**

c. What is the average number of games you play per week? ________

d. What is the average number of days between games? ______

10. During the off-season, how many hours per week do you spend performing the following?
a. Playing lacrosse: _____**hrs./week**
b. Upper extremity training/conditioning: _____**hrs./week**

11. Estimate the typical number of shots you perform at or greater than 90% of maximal effort during the following:
a. Practice: _______**shots**
b. Competition/Game: _______**shots**

Part 3. Medical History

12. Are you allergic to adhesive tape or other adhesive products? **YES** **NO**
If **YES, explain**:

____

13. Have you ever had an upper or lower extremity surgery? **YES** **NO**
If **YES, explain**:

____

____

If YES, on what part(s)? **FOOT/ANKLE** **KNEE** **HIP** **BACK** **SHOULDER** **ELBOW** **WRIST** **HAND/FINGER**

If YES, how long ago? ______ **Years**

14. In the past year, have you had any injury to your upper or lower extremities that has caused you to miss a practice or game? **YES** **NO**
If **YES, explain**:

____

____

If YES, on what part(s)? **FOOT/ANKLE** **KNEE** **HIP** **BACK** **SHOULDER** **ELBOW** **WRIST** **HAND/FINGER**

15. Do you currently experience pain/stiffness in your ankle, knees, hips, back, shoulder or elbow before, during, or after lacrosse practice/game?
YES **NO**
If **YES, please explain** and continue:

____

____

If **NO, please sign on page 3**.

16. Have you changed your training/competition habits because of upper or lower extremity pain?
YES **NO**

If **YES, explain**:

____

____

IF you answered YES to question 15:
17. For how long have you been experiencing pain? (Indicate a number next to one category)
_____Years _____Months _____ Days

18. When you do experience pain, how would you describe the onset of pain? (Circle one)
SUDDEN GRADUAL

19. When you do experience pain, how is it related to activity? (Circle one)
ASSOCIATED WITH USE INTERMITTENT ALL THE TIME

20. Have your activities of daily living been effected by your pain? **YES NO**
If **YES, explain**:

____

____

21. Has your pain disrupted your sleep? **YES NO**
If **YES, explain**:

____

____

22. Have you sought medical consultation because of your pain? **YES NO**
If **YES, explain**:

____

____

23. Have you been given treatment for your pain? **YES NO**
If **YES, explain**:

____

____

24. When you do experience pain, what is the intensity of the pain (1= NO pain; 10= unbearable pain)?
NO PAIN UNBEARABLE PAIN

1 2 3 4 5 6 7 8 9 10

I hereby state, to the best of my knowledge, my answers to the above questions are complete and correct.

Signature of Participant (or parent/guardian):

____

Appendix B

AUBURN UNIVERSITY
COLLEGE OF EDUCATION

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

The Effect of Stride Foot Contact Positioning on Kinematics, Kinetics, and Performance Outcomes in Male Lacrosse Athletes

INFORMED CONSENT TO PARTICIPATE IN RESEARCH

Explanation and Purpose of the Research

You are being asked to participate in a research study for the Sports Medicine & Movement Group in the Department of Kinesiology by Dr. Gretchen Oliver. Before agreeing to participate in this study, it is vital that you understand certain aspects of what might occur. This statement describes the purpose, methodology, benefits, risks, discomforts, and precautions of this research. This statement describes your right to confidentiality and to discontinue your participation at any time during the course of this research without penalty or prejudice. No assurances or guarantees can be made concerning the results of this study.

This study is designed to examine the effect of foot contact positioning on overhand shot performance of male lacrosse players. To investigate this, joint kinematic (where your body segments are in space), kinetic (estimates of how much force is produced in these segments), temporal (timing of movement), isometric strength (ability to contract your muscle against resistance), shot velocity, shot accuracy, and range of motion data will be collected during shooting.

Research Procedures

To be considered for this study, you must be a lacrosse athlete between the ages of 19 – 30 and you must be injury, surgery, and free of pain for the last 6 months. You must also not have an allergy to adhesive tape. Shooting-side dominance will not be a selection factor for this study.

Testing in this research will require the evaluation of height, body mass, age, and range of motion. Body mass and height will be measured with Motion Monitor motion capture system and will be recorded to the nearest tenth of a kilogram and centimeter. Age will be determined from this consent form and will be recorded to the nearest month. Range of motion will be measured with a goniometer and will be recorded to the nearest degree.

Once all preliminary paperwork has been completed, you will need to be dressed loose fitting athletic attire, as well as protective padding (shoulder and elbow pads, gloves, and helmet) for testing. Range of motion of the shoulder and hip will first be measured and recorded. To measure shoulder range of motion, you will lay supine on the table with your arm hanging off the side at the shoulder. An investigator will hold your arm parallel to the ground with your elbow bent to ninety degrees. The investigator will then passively rotate your arm until maximal internal rotation is reached. This will then be repeated for maximal external rotation. For hip range of motion, you will sit on a table with your lower leg hanging off the side. An investigator will passively rotate your lower leg until maximal internal rotation is reached. This will then be repeated for maximal external rotation.

Similar procedures will be performed to measure isometric strength. To measure shoulder strength you will be positioned lying on a table with your upper arm parallel to the floor and elbow bent. You will then externally/internally rotate against the investigator for 5 seconds. The investigator will hold a hand held dynamometer against your forearm to record the force. In order to reduce the effects of fatigue a rest period of 20-30 seconds will be allotted between trials.

Next, electromagnetic sensors will be placed on your feet (top of shoes), legs (lateral side of lower legs and lateral side of upper legs/thighs), arms (lateral side of upper arms, forearms, and dominant side top of hand), torso (both scapulae/shoulder blades and the lower back), and neck (back side of the lower neck). Placement of the markers at these locations will allow the movement of the joint centers to be properly monitored during testing. Surface electromyography sensors will also be placed on your gluteus maximus (upper butt) and latissimus dorsi (mid/upper back) muscles to observe muscle activity during the overhand shot.

Once these measurements have been collected and following the placement of the markers, you will wear all of your protective gear and perform your own specified pre-competition warm-up routine for 5 minutes. During the warm-up period, we ask that you progress to maximal effort shots. After completing the warm-up, you will perform 5 overhand shots on each of the 4 corners (2 upper, 2 lower) of a standard lacrosse goal from 5 yards using your dominant shooting arm with your stride foot landing in three positions (closed, in-line, and open) on a force plate. You will perform a total of 60 maximal efforts overhand shots over the duration of the study.

Potential Risks

As with any movement research, certain risks and discomforts may arise. The possible risks and discomforts associated with this study are no greater than those involved in lacrosse shooting and may include: death, muscle strain, muscle soreness, ligament and tendon damage, and general overuse injury to the shooting lacrosse athlete. Every effort will be made to minimize these risks and discomforts. It is your responsibility, as a participant, to inform the investigators if you notice any indications of injury or fatigue, or feel symptoms of any other possible complications that might occur during testing.

To reduce the risk of injury, certain precautions will be taken. During the shooting protocol, two board certified athletic trainers will be present to monitor you as you shoot. Ample warm-up and cool-down periods will be required of you, water will be provided to you as needed, and ice will be made available after testing.

The researcher will try to prevent any problem that could happen because of this research. If at any time there is a problem you should let the researcher know and she will help you. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

Confidentiality

All information gathered in completing this study will remain confidential. Your individual performance will not be made available for public use, and will not be disclosed to any person(s) outside of the research team. The results of this study may be published as scientific research. Your name or identity shall not be revealed should such publication occur.

Participation and Benefits

Participation in this research is strictly voluntary and refusal to participate will result in no penalty. If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the School of Kinesiology.

By participating in this study, you will receive information regarding lacrosse shooting mechanics that may increase performance and help prevent injury. This will allow you the opportunity to alter your training programs in an effort to minimize injury resulting from improper mechanics, fatigue, etc.

Questions Regarding the Study

If you have questions about this study, please ask them now. If you have questions later you may contact Matthew Hanks, 616-644-3592 or mmh0033@auburn.edu.

If you have any questions about your rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or email at irbadmin@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

______________________________	______yr.______mo.
Printed Name of Participant	Age of Participant
______________________________	______________
Signature of Participant	Date

The above consent form was read, discussed, and signed in my presence. In my opinion, the person signing said consent form did so freely and with full knowledge of its contents.

______________________________	______________
Signature of Investigator, Matthew Hanks	Date

AUBURN UNIVERSITY

COLLEGE OF EDUCATION

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

Parental Permission/Minor Assent

The Effect of Stride Foot Contact Positioning on Kinematics, Kinetics, and Performance Outcomes in Male Lacrosse Athletes

CONSENT TO PARTICIPATE IN RESEARCH

Explanation and Purpose of the Research

Your child is being asked to participate in a research study for the Sports Medicine & Movement Group in the Department of Kinesiology by Dr. Gretchen Oliver. Before agreeing to participate in this study, it is vital that you and your child understand certain aspects of what might occur. This statement describes the purpose, methodology, benefits, risks, discomforts, and precautions of this research. This statement describes your right to confidentiality and your child’s right to discontinue their participation at any time during the course of this research without penalty or prejudice. No assurances or guarantees can be made concerning the results of this study.

This study is designed to examine the effect of foot contact positioning on overhand shot performance of male lacrosse players. To investigate this, joint kinematic (where your body segments are in space), kinetic (estimates of how much force is produced in these segments), temporal (timing of movement), isometric strength (ability to contract your muscle against resistance), shot velocity, shot accuracy, and range of motion data will be collected during shooting.

Research Procedures

To be considered for this study, your child must be a lacrosse athlete between the ages of 7 – 18 and your child must be injury, surgery, and free of pain for the last 6 months. Your child must also not have an allergy to adhesive tape. Shooting-side dominance will not be a selection factor for this study.

Testing in this research will require the evaluation of height, body mass, age, and range of motion. Body mass and height will be measured with Motion Monitor motion capture system and will be recorded to the nearest tenth of a kilogram and centimeter. Age will be determined from this consent form and will be recorded to the nearest month. Range of motion will be measured with a goniometer and will be recorded to the nearest degree.

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Similar procedures will be performed to measure isometric strength. To measure shoulder strength your child will be positioned lying on a table with their upper arm parallel to the floor and elbow bent. They will then externally/internally rotate against the investigator for 5 seconds. The investigator will hold a hand held dynamometer against their forearm to record the force. In order to reduce the effects of fatigue a rest period of 20-30 seconds will be allotted between trials.

Next, electromagnetic sensors will be placed on your child's feet (top of shoes), legs (lateral side of lower legs and lateral side of upper legs/thighs), arms (lateral side of upper arms, forearms, and dominant side top of hand), torso (both scapulae/shoulder blades and the lower back), and neck (back side of the lower neck). Placement of the markers at these locations will allow the movement of the joint centers to be properly monitored during testing. Surface electromyography sensors will also be placed on their gluteus maximus (upper butt) and latissimus dorsi (mid/upper back) muscles to observe muscle activity during the overhand shot.

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As with any movement research, certain risks and discomforts may arise. The possible risks and discomforts associated with this study are no greater than those involved in lacrosse shooting and may include: death, muscle strain, muscle soreness, ligament and tendon damage, and general overuse injury to the athlete. Every effort will be made to minimize these risks and discomforts. It is your child's responsibility, as a participant, to inform the investigators if they notice any indications of injury or fatigue, or feel symptoms of any other possible complications that might occur during testing.

To reduce the risk of injury, certain precautions will be taken. During the shooting protocol, two board certified athletic trainers will be present to monitor your child as they shoot. Ample warm-up and cool-down periods will be required of your child, water will be provided to your child as needed, and ice will be made available after testing.

The researcher will try to prevent any problem that could happen because of this research. If at any time there is a problem you should let the researcher know and she will help you. Should an emergency arise, we will call 911 and follow our Emergency Action Plan. In the unlikely event that you sustain an injury from participation in this study, the investigators have no current plans to provide funds for any medical expenses or other costs you may incur.

Confidentiality

All information gathered in completing this study will remain confidential. Your child's individual performance will not be made available for public use, and will not be disclosed to any person(s) outside of the research team. The results of this study may be published as scientific research. Your child's name or identity shall not be revealed should such publication occur.

Participation and Benefits

Participation in this research is strictly voluntary and refusal to participate will result in no penalty. If you or your child changes your mind about participating, they can withdraw at any time during the study. Your child's participation is completely voluntary. If you or your child chooses to withdraw, their data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize you or your child's future relations with Auburn University or the School of Kinesiology.

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Questions Regarding the Study

If you have questions about this study, please ask them now. If you have questions later you may contact Matthew Hanks, 616-644-3592 or mmh0033@auburn.edu.

If you have any questions about your child's rights as a research participant, you may contact the Auburn University Office of Research Compliance or the Institutional Review Board by phone (334)-844-5966 or email at irbadmin@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH FOR YOUR CHILD TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO ALLOW YOUR CHILD'S PARTICIPATION.

________________________________	______ yr. ______ mo.
Printed Name of Parent	Age of Participant
________________________________	________________
Signature of Parent	Date
________________________________	
Printed Name of Participant	
________________________________	________________
Signature of Participant	Date

The above consent form was read, discussed, and signed in my presence. In my opinion, the person signing said consent form did so freely and with full knowledge of its contents.

Signature of Investigator, Matthew Hanks Date

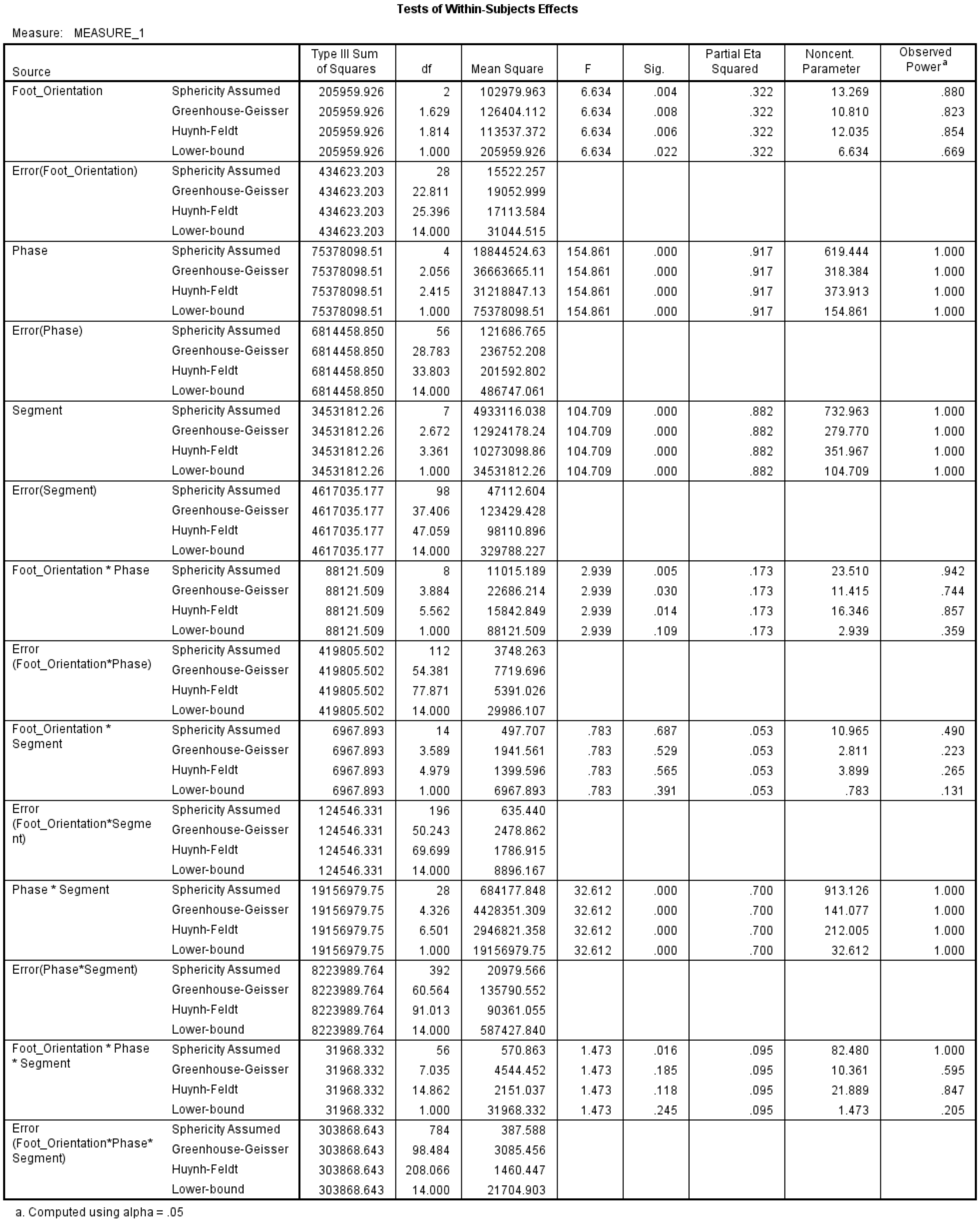
Appendix C

Borg's Rating of Perceived Exertion (RPE) Scale (1998)[99]

Rating	Perceived Exertion
6	No exertion
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Appendix D

Research Question 1. Does stride foot contact orientation affect the average angular velocities of the pelvis, trunk, and bilateral upper extremities during the phases of the overhand lacrosse shot?



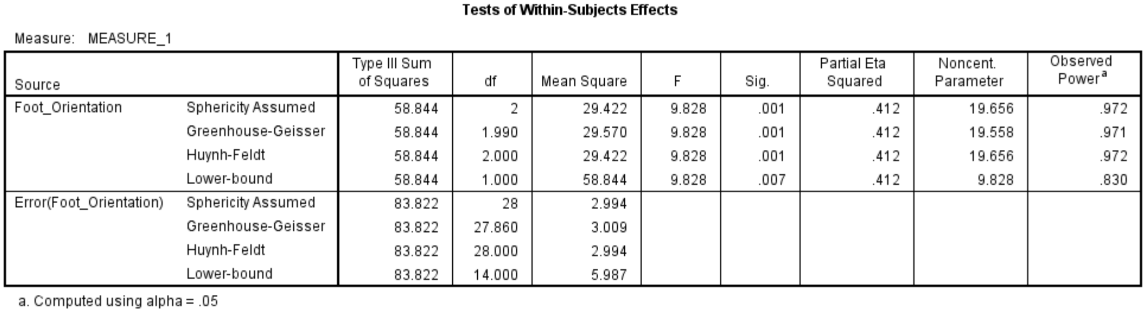
Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Foot_Orientation	Sphericity Assumed	205959.926	2	102979.963	6.634	.004	.322	13.269	.880
	Greenhouse-Geisser	205959.926	1.629	126404.112	6.634	.008	.322	10.810	.823
	Huynh-Feldt	205959.926	1.814	113537.372	6.634	.006	.322	12.035	.854
	Lower-bound	205959.926	1.000	205959.926	6.634	.022	.322	6.634	.669
Error(Foot_Orientation)	Sphericity Assumed	434623.203	28	15522.257					
	Greenhouse-Geisser	434623.203	22.811	19052.999					
	Huynh-Feldt	434623.203	25.396	17113.584					
	Lower-bound	434623.203	14.000	31044.515					
Phase	Sphericity Assumed	75378098.51	4	18844524.63	154.861	.000	.917	619.444	1.000
	Greenhouse-Geisser	75378098.51	2.056	36663665.11	154.861	.000	.917	318.384	1.000
	Huynh-Feldt	75378098.51	2.415	31218847.13	154.861	.000	.917	373.913	1.000
	Lower-bound	75378098.51	1.000	75378098.51	154.861	.000	.917	154.861	1.000
Error(Phase)	Sphericity Assumed	6814458.850	56	121686.765					
	Greenhouse-Geisser	6814458.850	28.783	236752.208					
	Huynh-Feldt	6814458.850	33.803	201592.802					
	Lower-bound	6814458.850	14.000	486747.061					
Segment	Sphericity Assumed	34531812.26	7	4933116.038	104.709	.000	.882	732.963	1.000
	Greenhouse-Geisser	34531812.26	2.672	12924178.24	104.709	.000	.882	279.770	1.000
	Huynh-Feldt	34531812.26	3.361	10273098.86	104.709	.000	.882	351.967	1.000
	Lower-bound	34531812.26	1.000	34531812.26	104.709	.000	.882	104.709	1.000
Error(Segment)	Sphericity Assumed	4617035.177	98	47112.604					
	Greenhouse-Geisser	4617035.177	37.406	123429.428					
	Huynh-Feldt	4617035.177	47.059	98110.896					
	Lower-bound	4617035.177	14.000	329788.227					
Foot_Orientation * Phase	Sphericity Assumed	88121.509	8	11015.189	2.939	.005	.173	23.510	.942
	Greenhouse-Geisser	88121.509	3.884	22686.214	2.939	.030	.173	11.415	.744
	Huynh-Feldt	88121.509	5.562	15842.849	2.939	.014	.173	16.346	.857
	Lower-bound	88121.509	1.000	88121.509	2.939	.109	.173	2.939	.359
Error (Foot_Orientation*Phase)	Sphericity Assumed	419805.502	112	3748.263					
	Greenhouse-Geisser	419805.502	54.381	7719.696					
	Huynh-Feldt	419805.502	77.871	5391.026					
	Lower-bound	419805.502	14.000	29986.107					
Foot_Orientation * Segment	Sphericity Assumed	6967.893	14	497.707	.783	.687	.053	10.965	.490
	Greenhouse-Geisser	6967.893	3.589	1941.561	.783	.529	.053	2.811	.223
	Huynh-Feldt	6967.893	4.979	1399.596	.783	.565	.053	3.899	.265
	Lower-bound	6967.893	1.000	6967.893	.783	.391	.053	.783	.131
Error (Foot_Orientation*Segment)	Sphericity Assumed	124546.331	196	635.440					
	Greenhouse-Geisser	124546.331	50.243	2478.862					
	Huynh-Feldt	124546.331	69.699	1786.915					
	Lower-bound	124546.331	14.000	8896.167					
Phase * Segment	Sphericity Assumed	19156979.75	28	684177.848	32.612	.000	.700	913.126	1.000
	Greenhouse-Geisser	19156979.75	4.326	4428351.309	32.612	.000	.700	141.077	1.000
	Huynh-Feldt	19156979.75	6.501	2946821.358	32.612	.000	.700	212.005	1.000
	Lower-bound	19156979.75	1.000	19156979.75	32.612	.000	.700	32.612	1.000
Error(Phase*Segment)	Sphericity Assumed	8223989.764	392	20979.566					
	Greenhouse-Geisser	8223989.764	60.564	135790.552					
	Huynh-Feldt	8223989.764	91.013	90361.055					
	Lower-bound	8223989.764	14.000	587427.840					
Foot_Orientation * Phase * Segment	Sphericity Assumed	31968.332	56	570.863	1.473	.016	.095	82.480	1.000
	Greenhouse-Geisser	31968.332	7.035	4544.452	1.473	.185	.095	10.361	.595
	Huynh-Feldt	31968.332	14.862	2151.037	1.473	.118	.095	21.889	.847
	Lower-bound	31968.332	1.000	31968.332	1.473	.245	.095	1.473	.205
Error (Foot_Orientation*Phase*Segment)	Sphericity Assumed	303868.643	784	387.588					
	Greenhouse-Geisser	303868.643	98.484	3085.456					
	Huynh-Feldt	303868.643	208.066	1460.447					
	Lower-bound	303868.643	14.000	21704.903					

a. Computed using alpha = .05

Research Question 2. Does stride foot contact orientation affect ball velocity?



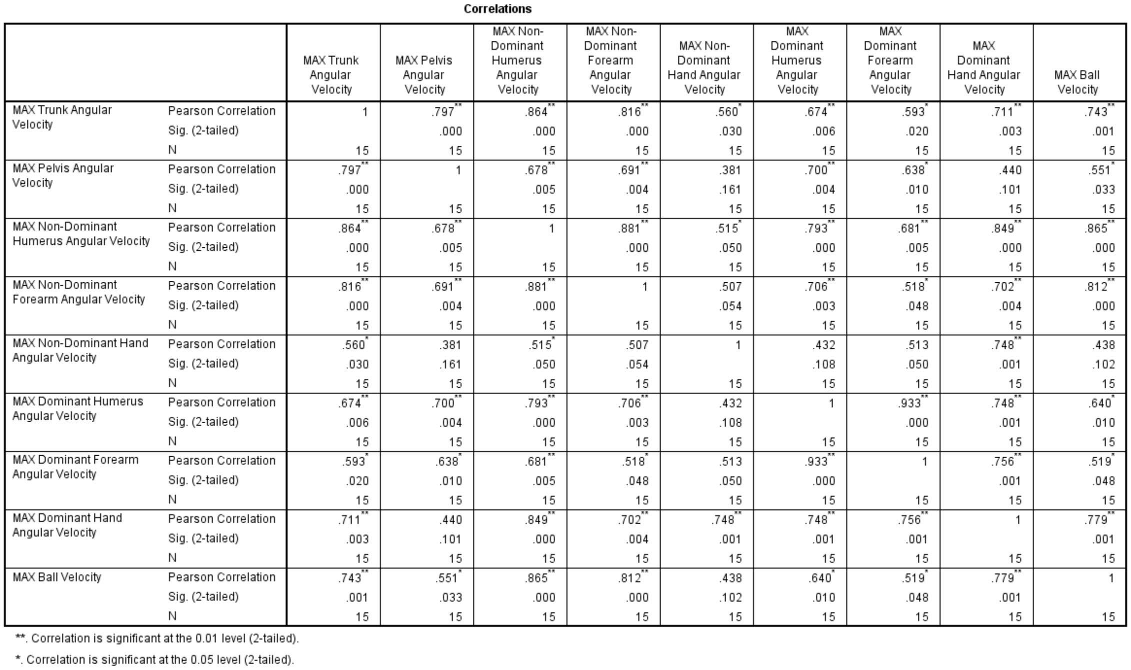
Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Foot_Orientation	Sphericity Assumed	58.844	2	29.422	9.828	.001	.412	19.656	.972
	Greenhouse-Geisser	58.844	1.990	29.570	9.828	.001	.412	19.558	.971
	Huynh-Feldt	58.844	2.000	29.422	9.828	.001	.412	19.656	.972
	Lower-bound	58.844	1.000	58.844	9.828	.007	.412	9.828	.830
Error(Foot_Orientation)	Sphericity Assumed	83.822	28	2.994					
	Greenhouse-Geisser	83.822	27.860	3.009					
	Huynh-Feldt	83.822	28.000	2.994					
	Lower-bound	83.822	14.000	5.987					

a. Computed using alpha = .05

Research Question 3. Is there a correlation between maximum angular velocities of the pelvis, trunk, and bilateral upper extremities and ball velocity during the phases of the overhand lacrosse shot?



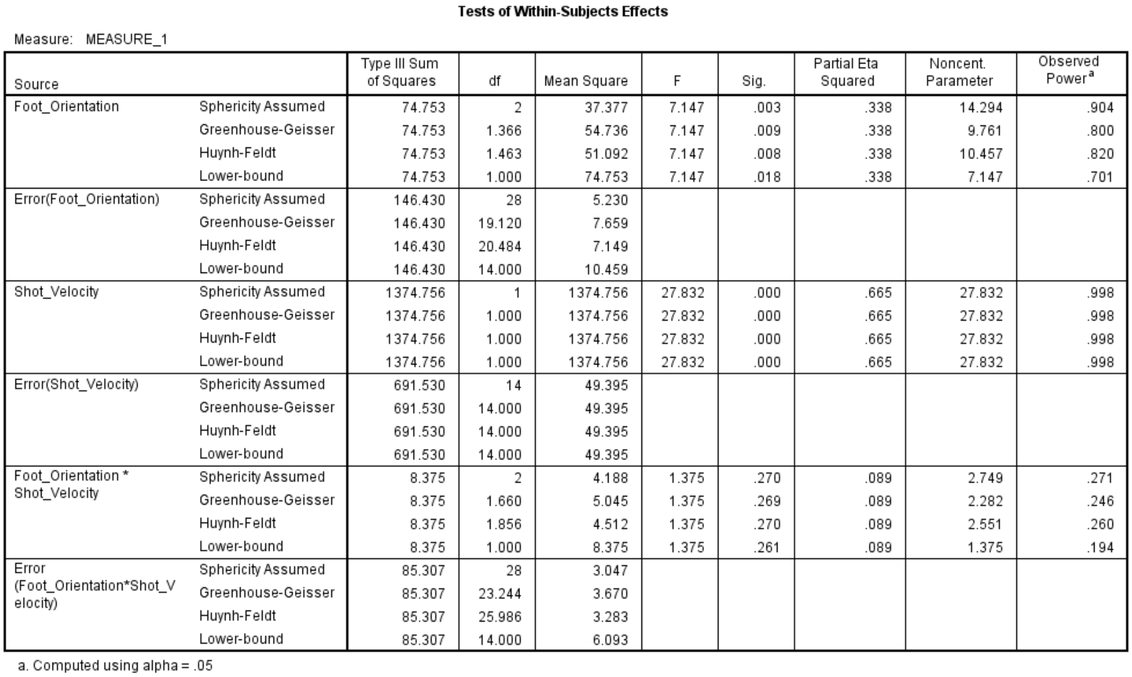
Correlations

		MAX Trunk Angular Velocity	MAX Pelvis Angular Velocity	MAX Non-Dominant Humerus Angular Velocity	MAX Non-Dominant Forearm Angular Velocity	MAX Non-Dominant Hand Angular Velocity	MAX Dominant Humerus Angular Velocity	MAX Dominant Forearm Angular Velocity	MAX Dominant Hand Angular Velocity	MAX Ball Velocity
MAX Trunk Angular Velocity	Pearson Correlation	1	.797**	.864**	.816**	.560*	.674**	.593*	.711**	.743**
	Sig. (2-tailed)		.000	.000	.000	.030	.006	.020	.003	.001
	N	15	15	15	15	15	15	15	15	15
MAX Pelvis Angular Velocity	Pearson Correlation	.797**	1	.678**	.691**	.381	.700**	.638*	.440	.551*
	Sig. (2-tailed)	.000		.005	.004	.161	.004	.010	.101	.033
	N	15	15	15	15	15	15	15	15	15
MAX Non-Dominant Humerus Angular Velocity	Pearson Correlation	.864**	.678**	1	.881**	.515*	.793**	.681**	.849**	.865**
	Sig. (2-tailed)	.000	.005		.000	.050	.000	.005	.000	.000
	N	15	15	15	15	15	15	15	15	15
MAX Non-Dominant Forearm Angular Velocity	Pearson Correlation	.816**	.691**	.881**	1	.507	.706**	.518*	.702**	.812**
	Sig. (2-tailed)	.000	.004	.000		.054	.003	.048	.004	.000
	N	15	15	15	15	15	15	15	15	15
MAX Non-Dominant Hand Angular Velocity	Pearson Correlation	.560*	.381	.515*	.507	1	.432	.513	.748**	.438
	Sig. (2-tailed)	.030	.161	.050	.054		.108	.050	.001	.102
	N	15	15	15	15	15	15	15	15	15
MAX Dominant Humerus Angular Velocity	Pearson Correlation	.674**	.700**	.793**	.706**	.432	1	.933**	.748**	.640*
	Sig. (2-tailed)	.006	.004	.000	.003	.108		.000	.001	.010
	N	15	15	15	15	15	15	15	15	15
MAX Dominant Forearm Angular Velocity	Pearson Correlation	.593*	.638*	.681**	.518*	.513	.933**	1	.756**	.519*
	Sig. (2-tailed)	.020	.010	.005	.048	.050	.000		.001	.048
	N	15	15	15	15	15	15	15	15	15
MAX Dominant Hand Angular Velocity	Pearson Correlation	.711**	.440	.849**	.702**	.748**	.748**	.756**	1	.779**
	Sig. (2-tailed)	.003	.101	.000	.004	.001	.001	.001		.001
	N	15	15	15	15	15	15	15	15	15
MAX Ball Velocity	Pearson Correlation	.743**	.551*	.865**	.812**	.438	.640*	.519*	.779**	1
	Sig. (2-tailed)	.001	.033	.000	.000	.102	.010	.048	.001	
	N	15	15	15	15	15	15	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Research Question 4. Is a speed-accuracy tradeoff present in the overhand lacrosse shot?



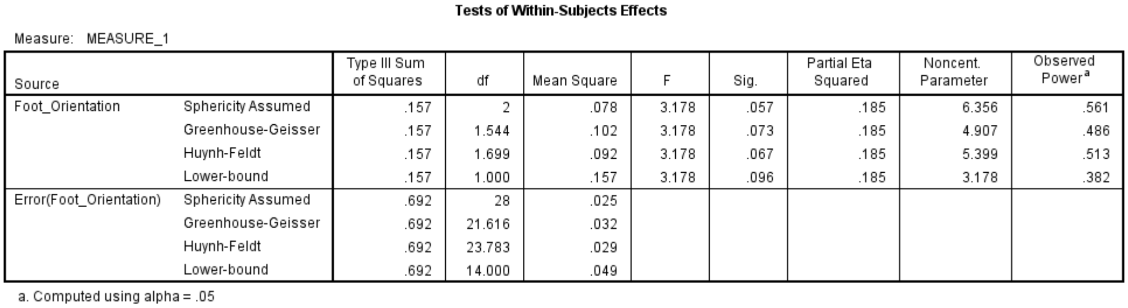
Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Foot_Orientation	Sphericity Assumed	74.753	2	37.377	7.147	.003	.338	14.294	.904
	Greenhouse-Geisser	74.753	1.366	54.736	7.147	.009	.338	9.761	.800
	Huynh-Feldt	74.753	1.463	51.092	7.147	.008	.338	10.457	.820
	Lower-bound	74.753	1.000	74.753	7.147	.018	.338	7.147	.701
Error(Foot_Orientation)	Sphericity Assumed	146.430	28	5.230					
	Greenhouse-Geisser	146.430	19.120	7.659					
	Huynh-Feldt	146.430	20.484	7.149					
	Lower-bound	146.430	14.000	10.459					
Shot_Velocity	Sphericity Assumed	1374.756	1	1374.756	27.832	.000	.665	27.832	.998
	Greenhouse-Geisser	1374.756	1.000	1374.756	27.832	.000	.665	27.832	.998
	Huynh-Feldt	1374.756	1.000	1374.756	27.832	.000	.665	27.832	.998
	Lower-bound	1374.756	1.000	1374.756	27.832	.000	.665	27.832	.998
Error(Shot_Velocity)	Sphericity Assumed	691.530	14	49.395					
	Greenhouse-Geisser	691.530	14.000	49.395					
	Huynh-Feldt	691.530	14.000	49.395					
	Lower-bound	691.530	14.000	49.395					
Foot_Orientation * Shot_Velocity	Sphericity Assumed	8.375	2	4.188	1.375	.270	.089	2.749	.271
	Greenhouse-Geisser	8.375	1.660	5.045	1.375	.269	.089	2.282	.246
	Huynh-Feldt	8.375	1.856	4.512	1.375	.270	.089	2.551	.260
	Lower-bound	8.375	1.000	8.375	1.375	.261	.089	1.375	.194
Error (Foot_Orientation*Shot_Velocity)	Sphericity Assumed	85.307	28	3.047					
	Greenhouse-Geisser	85.307	23.244	3.670					
	Huynh-Feldt	85.307	25.986	3.283					
	Lower-bound	85.307	14.000	6.093					

a. Computed using alpha = .05

Research Question 5. How does stride foot contact orientation affect ankle and knee joint moments throughout the shooting motion?

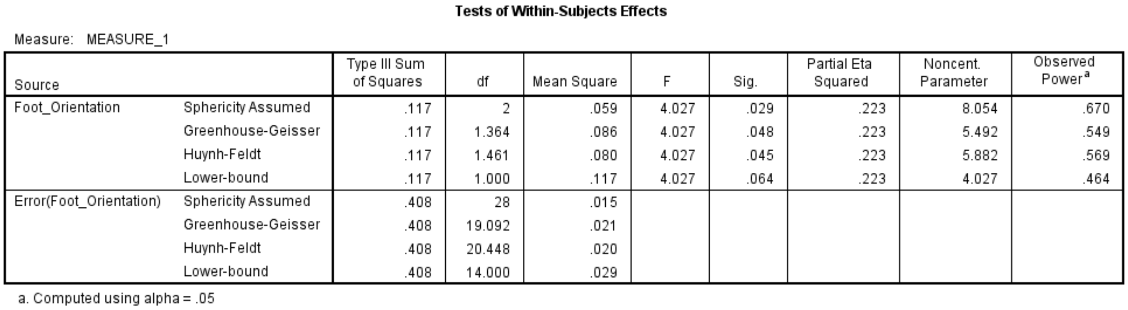


Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Foot_Orientation	Sphericity Assumed	.157	2	.078	3.178	.057	.185	6.356	.561
	Greenhouse-Geisser	.157	1.544	.102	3.178	.073	.185	4.907	.486
	Huynh-Feldt	.157	1.699	.092	3.178	.067	.185	5.399	.513
	Lower-bound	.157	1.000	.157	3.178	.096	.185	3.178	.382
Error(Foot_Orientation)	Sphericity Assumed	.692	28	.025					
	Greenhouse-Geisser	.692	21.616	.032					
	Huynh-Feldt	.692	23.783	.029					
	Lower-bound	.692	14.000	.049					

a. Computed using alpha = .05



Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Foot_Orientation	Sphericity Assumed	.117	2	.059	4.027	.029	.223	8.054	.670
	Greenhouse-Geisser	.117	1.364	.086	4.027	.048	.223	5.492	.549
	Huynh-Feldt	.117	1.461	.080	4.027	.045	.223	5.882	.569
	Lower-bound	.117	1.000	.117	4.027	.064	.223	4.027	.464
Error(Foot_Orientation)	Sphericity Assumed	.408	28	.015					
	Greenhouse-Geisser	.408	19.092	.021					
	Huynh-Feldt	.408	20.448	.020					
	Lower-bound	.408	14.000	.029					

a. Computed using alpha = .05