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Drive Leg and Stride Leg Ground Reaction Forces Relationship to Medial Elbow Stress and Velocity in Collegiate Baseball Pitchers

Brett Smith
Old Dominion University, bsmit003@odu.edu

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DRIVE LEG AND STRIDE LEG GROUND REACTION FORCES RELATIONSHIP TO MEDIAL ELBOW STRESS AND VELOCITY IN COLLEGIATE BASEBALL PITCHERS

by

Brett Smith
B.S. May 2019, Old Dominion University

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May 2021

Approved by:

Stacie Ringleb (Director)

Hunter Bennett (Member)

Sebastian Bawab (Member)

ABSTRACT

DRIVE LEG AND STRIDE LEG GROUND REACTION FORCES RELATIONSHIP TO MEDIAL ELBOW STRESS AND VELOCITY IN COLLEGIATE BASEBALL PITCHERS

Brett Kampen Smith
Old Dominion University, 2021
Advisor: Dr. Stacie Ringleb

This study examines several different kinetic variables in relation to pitch velocity and elbow varus torque in collegiate baseball pitchers using force plates, an inertial measurement unit, and a radar unit. The purpose of this study is to investigate the kinetic variables being measured and their relationship to pitch velocity and loads being placed on the medial elbow. Twelve collegiate baseball pitchers participated in this study, which was approved by the IRB. Impulse of the drive leg in the anterior-posterior direction, stride leg peak force in the anterior-posterior (AP) direction, elbow varus torque, and pitch velocity were all measured. Two video cameras were used to record the pitching mechanics of each participant with their consent. Two force plates (2000Hz, Bertec FP-4060, Bertec Inc., OH, USA) were used to measure drive leg and stride leg ground reaction forces. An inertial measurement unit (motusBASEBALL Complete Package, Motus Global Inc., Massapequa, NY) was used to measure elbow torque. A radar unit (Rapsodo Pitching 2.0, Rapsodo Pte Ltd., Brentwood, MO) was used to measure pitch velocity. Pearson product-moment correlations were performed for each research question; the correlation coefficient (r) and p-values were reported for each. The strength of association was considered small for values of the correlation coefficient between 0.1 to 0.3, medium for values between 0.3 to 0.5, and large for values between 0.5 to 1.0. The a priori alpha level was set to 0.05. Impulse of the drive leg in the AP direction was significantly related to increased pitch velocity with an association of medium strength (p-value < 0.001, $r = 0.366$) and inversely related

to elbow varus torque with a small association of strength (p-value=0.001, r = 0.299). Stride leg peak force in the AP direction was significantly related to increased pitch velocity (p-value=0.013, r = 0.222). Increasing the impulse on the drive leg in the AP direction may lead to greater pitch velocity and a decrease in elbow varus torque. Additionally, increasing stride leg peak ground reaction forces in the AP direction may lead to greater pitch velocity.

I dedicate this thesis to my mother and father for their continuous support and encouragement for me to pursue my goals and aspirations. This is also dedicated to the surgeons, physical therapists, and coaches that I have encountered throughout my journey of injuries that have inspired me and have helped to fuse my passions of baseball, engineering, and helping people.

AKNOWLEDGMENTS

I would like to thank my advisors, Dr. Stacie Ringleb, Dr. Hunter Bennett, and Dr. Sebastian Bawab for guiding me throughout this research and the opportunity to study one of my passions. I would like to thank Eva Maddox for all her time spent assisting and mentoring me throughout the process as well as help with data collection and processing. I would like to thank my coaches for their commitment, ideas, and allowing me to collect data on the pitchers. Finally, I would like to thank my dad for the countless hours spent helping me construct the mound.

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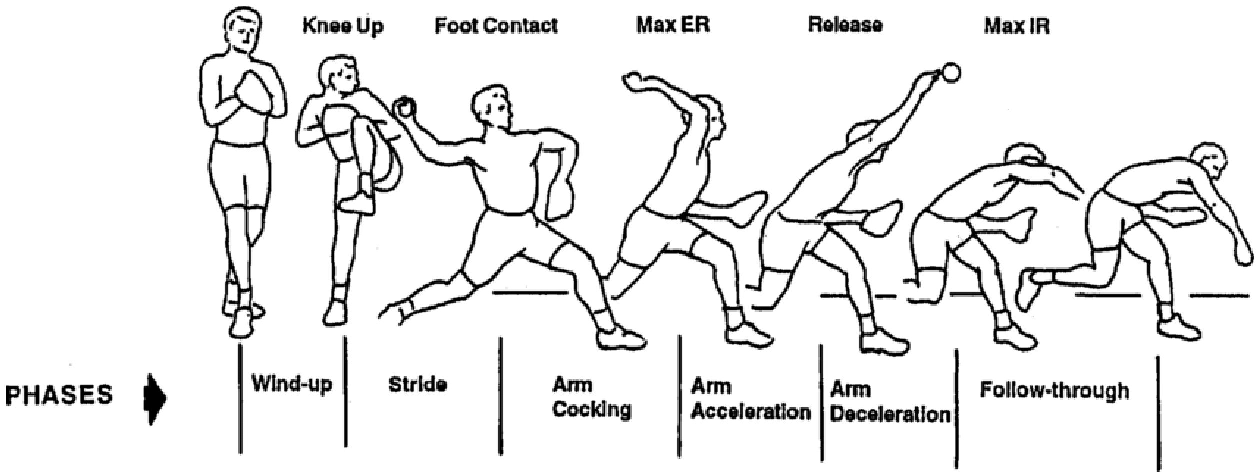
CHAPTER I

INTRODUCTION

Baseball pitching is an athletic movement that requires the transfer of energy from the lower extremity to the upper extremity in a complex, yet highly coordinated sequence of movements. Baseball is the only throwing sport that uses an elevated pitching mound; baseball pitching compels the pitcher to generate and dissipate ground reaction forces [1]. The pitching motion is a very dynamic movement that can cause high amounts of stress leading to a high prevalence of injuries on various joints including, but not limited to, the elbow, shoulder, and soft tissue that surrounds and supports these joints [2]–[4].

The pitching motion can be broken down into six different phases: the wind up, stride, arm cocking, arm acceleration, arm declaration, and follow through as seen in Figure 1 [5]. At the start of a pitcher's motion, the transfer of energy starts in the wind-up phase when the pitcher lifts their stride leg and loads their weight and force into their drive leg. The wind-up phase begins from the first motion of the pitcher while on the rubber and ends at peak knee lift of the stride leg [6]. The stride phase follows with the separating of the hands and lowering of the stride leg down and toward home plate until reaching foot contact [6]. The arm cocking phase follows with the pelvis and upper trunk rotating towards the target while the arm cocks back until reaching maximum external rotation [6]. The arm acceleration phase follows as the arm begins to accelerate reaching maximum elbow extension velocity of about 2500 degrees per second and maximum shoulder internal rotation velocity of about 7500 degrees per second and ends at ball release [6]. An important factor during ball release is the planting of the stride leg to transfer energy from the ground up to the ball. The knee of the stride leg extends to stop the acceleration of the pelvis forward and the rapid rotations of the trunk and throwing arm result in forces greater than body weight at the shoulder and elbow to prevent distraction [6]. The arm deceleration phase starts after the ball is released as the arm rotates internally and the forearm begins to pronate [6]. The arm adducts in front of the chest and back leg steps forward as the energy is dissipated [6].

Figure 1. The six phases of the pitching motion. Basic key movements during the pitching motion with proper pitching mechanics. (Modified with permission from Fleisig et al. 1996.)



The pitching motion is a complex sequence of events that must be timed correctly and can place a large amount of force on joints. Variations from proper pitching mechanics are correlated with decreased pitch velocity and increased shoulder and elbow kinetics [6]. Injuries to a pitcher's throwing arm have continued to rise, and injuries are starting to become more prevalent in pitchers at an earlier age [7]. The incidence of elbow ulnar collateral ligament surgeries in collegiate baseball players was found to be 2.5 per 100 player-seasons for all players and was significantly higher among pitchers (4.4/100 player-seasons) than nonpitchers (0.7/100 player-seasons)[8]. Additionally, a significant correlation between maximum pitch velocity and elbow injury was found in professional baseball pitchers [9]. Many different theories exist as to how these injuries continue to become more prevalent. One theory is that athletes are specializing in sports at earlier ages and, in particular, more baseball pitchers are throwing all year long [10]. The frequency of arm injuries was found to be much higher in players specializing in only baseball than nonspecialized players [10]. Some studies suggest that poor pitching mechanics may lead to an increase in elbow torque and an increase in risk of injury [3], [8], [11]–[13]. Another study suggests that injuries are so prevalent due to a combination of over usage, fatigue, and improper throwing mechanics [4]. One study found a significant correlation between maximum pitch velocity and elbow injury in professional baseball pitchers [9].

Some studies have investigated the correlation between pitch velocity and elbow torque [9], [11], [14]–[16]. A study of 67 collegiate baseball pitchers using motion analysis found no significant association between pitch velocity and elbow torque [14]. Manipulation of biomechanical parameters such as late trunk rotation, reduced shoulder external rotation, and increased elbow flexion may decrease the magnitude of torque on the elbow [11]. A study using video analysis found a significant correlation relating elbow injury to elbow torque during the late arm cocking phase in a group of 23 professional pitchers [11]. Additionally, the three professional pitchers with the highest ball velocity were the three pitchers that required surgery to their elbow, and pitch velocity was concluded to be a distinct independent risk factor for elbow injury [11].

Ground reaction force profiles of athletes during a countermovement jump have been used to help analyze athlete’s athletic performance and risk of injury [17]. Elbow injury risk has been found to be highly related on ground reaction force data obtained during the counter movement jump of professional baseball pitchers [17]. In particular, pitchers who rely too much or too little on impulse momentum compared to force production during a counter movement jump were three times as likely to sustain elbow injuries compared to pitchers with more balanced profiles [17]. The pitchers that had sharp spikes on their force curves produced a large amount of force over a short period of time which tends to put more stress on distal joints such as the elbow and place them at a higher risk for injury [17]. The other high risk group relied too heavily on impulse-momentum to compensate for eccentric and concentric strength deficiencies and prolonged their force to compensate [17]. Pitchers with a balance between impulse and large amplitudes on counter movement jump profiles were found to absorb stresses more efficiently by distributing loads across different neuromuscular mechanisms [17]. Creating efficient movements to maximize force production and impulse as well as to dissipate those forces produced are important to reduce the risk of injury.

The production of peak ground reaction forces has been investigated in relation to pitch velocity and elbow injuries. In a study of adult recreational pitchers, peak stride leg ground reaction force during the arm-cocking phase was found to be the best predictor of pitch velocity ($r = 0.78$) among drive and stride leg ground reaction forces [18]. A study of collegiate baseball pitchers found braking force of the stride leg during the arm cocking phase related to pitch velocity [19]. Matsuo et al. found low braking force of the stride leg during the arm cocking phase and a short stride related to decreased pitch velocity [2]. Stride leg knee extension angular velocity at ball release was significantly related to increased pitch velocity in collegiate and professional baseball pitchers [2]. A study of 24 youth baseball pitchers discovered that peak braking ground reaction force of the stride leg correlated with energy flow into the arm ($r = 0.629$) and helped generate rotational power transferred between the trunk and arm segment via the shoulder joint [20]. Peak ground reaction force of the drive leg during the stride phase correlated with energy flow across the pelvis (r = 0.544) and trunk segments (r = 0.619) [20]. Kageyama et al. found maximum stride leg ground reaction force was significantly greater in a high-ball-velocity group versus a low-ball velocity group [12]. The majority of research has focused on the peak ground reaction forces of the drive or stride leg and the relationship with pitch velocity. However, limited research exists that focuses on the impulse of the ground reaction forces and their relation to pitch velocity and injury.

While peak ground reaction forces explain part of the relationship to pitch velocity and elbow stress, impulse of the drive leg may play a more significant role. Peak ground reaction forces for the drive and stride leg were found to relate to energy flow, defined as the transfer of mechanical energy between body segments, in a few segments of the trunk and arm; however, impulse of the drive and stride leg were significantly related to all energy flow variables [20]. Ground reaction force impulse of the drive leg contributed to energy flow between major segments of the lower and upper extremity [20]. Propulsion kinetics of the drive leg contributed to the transfer of linear power via the pelvis and trunk segments to the direction of the pitch [20]. Peak stride leg ground reaction forces have been observed to be significantly correlated to pitch velocity (r = 0.75) while peak drive leg ground reaction forces have been observed to have no correlation to pitch velocity (r = 0.04) in youth pitchers [18]. Peak ground reaction forces only explain part of the relationship to pitch velocity, and impulse of the drive leg and its ability to generate linear momentum should be further investigated [18].

Ground reaction forces play an important role in generating energy with the lower extremity to transfer to the trunk and upper extremity. Both the drive and stride leg play key roles in force production and must work together to contribute to optimal kinetics and reduce the risk of injury. Kinematic and kinetic variables are often analyzed to investigate their relationship to kinetics on high-risk areas of anatomy in pitchers. Variations from proper pitching mechanics have been associated with increased shoulder and elbow kinetics [6]. Upper extremity kinematic studies using motion analysis have found significant relationships between pitch velocity and kinetics at the shoulder and elbow [21]–[23]. However, limited research exists on the lower extremity's role in force production and transferring the energy to the upper extremity. A better understanding of lower extremity movements and kinetics may result in an increase in pitch velocity while minimizing elbow varus torque in pitchers. Understanding the relationship between the lower extremity kinetics, elbow varus torque, and pitch velocity may lead to a decrease in loads on upper extremity joints and maximize pitch velocity. Therefore, the purpose of this study is to determine correlations between lower extremity kinetic variables, pitch velocity and elbow varus torque. The following hypotheses were developed:

> Hypothesis 1: There will be a direct correlation between impulse of the drive leg in the anterior-posterior direction and pitch velocity.
>
> Hypothesis 2: There will be an inverse correlation between impulse of the drive leg in the anterior-posterior direction and elbow varus torque.
>
> Hypothesis 3: There will be a direct correlation between stride leg peak ground reaction force in the anterior-posterior direction and pitch velocity.

CHAPTER II

METHODS

Participants

The recruitment of participants and protocol for this study were approved by the Old Dominion University Institutional Review Board, the head baseball coach, and athletic director. Informed consent was obtained from the participants before any procedures were performed. Twelve participants (n=12, 10 right-handed, 2 left-handed, age: 20.6 ± 1.6, height: 187.0 ± 5.6 cm, mass: 91.9 ± 10.9 kg, and Body Mass Index: 26.16 ± 2.35 kg/m^2) were recruited to participate in this study and included in the statistical analysis. Participants were recruited primarily by word of mouth. Participants were included in the study if they were 18-30 years of age, a collegiate baseball pitcher, and able to throw 10 fastballs in a single testing session. Participants were excluded if there was any history of surgery in the past 12-months or any recent injury to the lower or upper extremity in the previous 3-months. Data collection for each subject from warm-up to completion of data collection was approximately 60 minutes.

Building the Mound

An instrumented pitching mound was built in accordance with the Major League Baseball (Major League Baseball, New York, NY) guidelines and specifications. However, due to the depth of the force plate at the front end of the mound, the height of the mound was raised 4 inches so the height of the shelf of the pitching mound was 14 inches instead of 10 inches. The 9-pocket net the pitchers threw at was raised by 4 inches to maintain throwing mechanics while on the higher mound. The slope of the mound decreased one inch for every foot in length, which gave an angle of slope of 4.76 degrees and is consistent with Major League Baseball's specifications. Two force plates (2000Hz, Bertec FP-4060, Bertec Inc., OH, USA) measuring 15 3/4 inches x 23 5/8 inches were used. One force plate was located under the pitching rubber on the flat portion of the mound for the drive leg. The other force plate was located in the landing area for the stride leg. The landing area for the stride leg had two wooden plugs with artificial turf attached to the top of it to accommodate different pitchers' stride lengths. The artificial turf had a low nap to increase traction and minimize slippage.

Plywood sheets that were 3/4-inch thick were used to create the structure of the instrumented pitching mound. The plywood was used vertically on edge for most of the structure to maximize strength. The sloping portion of the mound was built first and is shown in Figure 2. Four stringers running vertically provided structural rigidity and were cut with a table saw (Delta Shopmaster 10-inch Table Saw, Delta Power Equipment Corporation, Spartanburg County, SC) with the proper sloping angle of one inch for every foot in length. Each stringer was precisely 95 1/4-inch long with the height at the tall end reaching 14 inches and the height at the short end reaching 6 inches. Two sections were cut to fit on the ends of the stringers. One section was cut to be 48 inches x 14 inches and the other cut to be 48 inches x 6 inches. These sections and all proceeding sections were glued together with construction adhesive (Gorilla Max Strength Construction Adhesive, Gorilla Glue, Sharonville, Ohio) and secured with wood screws (Deckmate star drive coated screws, Home Depot, Atlanta, GA) using predrilled holes to prevent the wood from splitting. The two outer stringers and outer perpendicular sections were clamped with 90-degree corner clamps (Pony Jorgensen 3 inch 90-degree Corner Clamps, Pony Jorgenson, Saddle Brooke, NJ). Next, the two inside stringers were centered and placed 16 1/4-inch apart to leave a small 1/4-inch gap between the outer edges of the force plate and the mound to prevent unnecessary noise and vibrations from reaching the force plate. This area between the middle stringers provided a track where the force plate could move closer and further from the rubber to accommodate different pitchers' stride lengths. Two cross ribs were cut and attached between the middle stringers to provide support and keep the long sheets of plywood from bending. Steel corner supports were placed in the outer corners to provide strength and structural support.

Figure 2. Mound Framework for sloping section. The mound framework was built to Major League Baseball standards and made out of 3/4 inch plywood.

Next, the top flat portion of the mound was constructed. This section was precisely 24 inches x 48 inches when viewed from above. The back section was cut to be 48 inches x 14 inches, and the 4 stingers running parallel with the other stringers were cut to be 22 1/2 inches x 14 inches. The two middle stringers were centered and placed 24 1/8 inches apart. A cross rib was cut and attached between the middle stringers in a perpendicular direction. The two middle stringers and cross rib provided the area for the force plate to sit while leaving a small 1/4-inch gap between the outer edges of the force plate and mound. This section was attached to the previously described sloping section shown in Figure 3 and secured with construction adhesive and 2 1/2 inch screws drilled at an angle using a pocket hole jig (General EZ Pro Deluxe Pocket Hole Jig Kit, General Tools & Instruments LLC, Secaucus, NJ). To make a secure connection to the sloping section, pre-punched angle iron was secured to the inside corners with construction adhesive and was then bolted to the corners using 1 1/4 inch length 3/8-inch bolts with washers and nylon lock nuts.

Figure 3. Mound framework - flat shelf section attached to the sloping section. The flat shelf section was attached to the sloping section with pre-punched angle iron and secured with 1 1/4-inch bolts.

Next, the sections where each force plate sat were finalized. In the sloping landing area, two stringers were created with the same degree of slope but were offset from the top to accommodate the depth of the force plate and ensure the top of the force plate would sit flush when adding the 3/4-inch-thick plywood sheet over top of the skeleton structure. Two stringers with these dimensions were added to the inside section of each of the large stringers. Two cross ribs were added at the top and bottom of this section and a belt sander (Black & Decker 3 in x 21 in Belt Sander, Stanley Black & Decker, New Britain, CT) was used to ensure proper dimensions. These stringers and ribs were secured with construction adhesive and 2-inch wood screws. A tape measure and the force plate itself were used to confirm the force plate would sit flush with the rest of the mound. A portion of extruded aluminum angle was placed over top of the wooden stringer on each side to help accommodate the correct depth and ensure smoothness. Holes were predrilled (DEWALT 20V Max Cordless Drill, DEWALT, Baltimore, MD) into sections of the angle iron and then each piece was secured onto the top portion of the stringer for the force plate to sit on. The same process was used to create the sections for the force plate in the flat portion of the mound. However, these sections did not need to slope, and an aluminum angle was not used.

The skeleton structure was then placed on dollies, and a large 4 feet x 8 feet section of 3/4-inch thick plywood was positioned over top of the sloping section of mound. A pen was used to mark the sheet of plywood from underneath and then cut using a circular saw (DEWALT 71/4 inch Circular Saw, DEWALT, Baltimore, MD). The sheet was placed on top of the sloping section and secured with construction adhesive and 2-inch wood screws shown in Figure 4. A belt sander was used to smooth and line up the edges. The same process was used with another sheet of plywood and the flat portion of the mound.

Figure 4. Mound surface structure. The mound surface structure was built with overlayed sheets of 3/4-inch thick plywood and cut using a circular saw.

In order to accommodate different pitchers' stride lengths, two wooden plugs were constructed that could be positioned in various configurations that would allow the force plate to move forward or backward so that the pitcher could land on the force plate without altering their mechanics. These blocks were made of 3 pieces of 2-inch x 8-inch blocks of wood stacked on top of each other. An additional piece of wood was measured and added to the top of the blocks to make it level with the rest of the mound. The bottom block of wood was offset by 1/4 inch to maintain spacing between the force plate. These plugs enabled the force plate to sit in 3 positions dependent upon the stride length of the pitcher (short, medium, or long) shown in Figure 5.

Figure 5. Location of the landing force plate. The force plate at the landing position sits on a track and can move to three different positions. The force plate was moved dependent upon whether the pitcher had a short (left), medium (middle), or long (right) stride length.

To accommodate access to the force plate's output connector, two holes were drilled with a circular drill bit (Milwaukee 2 1/8-inch Hole Saw Milwaukee Tool, Brookfield, WI) in the front of the mound as well as the front cross rib. Then, polymerizing vinyl chloride (PVC) pipes were measured, cut with a hand saw, and glued to provide a passage for a cord to be inserted from in front of the mound and into the running track where the landing force plate sits. One PVC pipe ran from the front of the mound to the bottom of the cross rib, while the other ran from the front of the mound to the top of the cross rib. This was to accommodate access to the force plate's output connector when it sits in the most forward position as well as when the force plate sits in the middle or furthest position from the front of the mound and a wooden plug blocks the entry of the cord. Another hole was drilled in the side of the mound and in one of the stingers using a jig saw (Ryobi Jig Saw 3-inch blade, Ryobi, Fuchu, Hiroshima, Japan) to accommodate access to the force plate under the pitching rubber. This hole was drilled large enough so a hand could be placed through and securely attach the cord to the output connector of the force plate.

Finally, the mound was placed on top of two dollies, and artificial turf (Grizzly Grass 0.375 inch pile height, TrafficMaster, Garden Grove, CA) was positioned over the mound and marked from underneath, then cut to the correct dimensions with a razor knife. Artificial turf adhesive (Robert’s 6700 indoor-outdoor carpet adhesive, Roberts Consolidated Industries, Henderson, NV), as recommended by the manufacturer (TrafficMaster, Garden Grove, CA), was spread onto the plywood with a 1/8-inch notched adhesive trowel, and the turf was rolled on and pressed onto the mound (Figure 6). In a similar process, the artificial turf was attached to the top of each force plate with construction adhesive to provide a more solid bond to the metal force plate.

Figure 6. Surfacing the mound with artificial turf. The mound was surfaced with artificial turf and attached using artificial turf adhesive. The turf had a low nap and provided optimal traction.

Laboratory Setup

Data collection took place outdoors at the Bud Metheny Baseball Complex at Old Dominion University. For each day of data collection, the following process was executed. The instrumented pitching mound was moved from an inside stored location nearby and placed on an area of artificial turf outdoors in the same location each day of data collection (Figure 7). Two (Bertec FP-4060, Bertec Inc. OH, USA) force plates, each attached to an approximately 50-kilogram steel plate, were lowered into the mound. A small steel crowbar was used to help align the force plate and secure it into the correct position, so the force plate did not touch any portion of the mound and had approximately a 1/4-inch gap between the force plate and the turf around it on all sides. The unloaded force plates were hardware and software zeroed prior to beginning the data collection. Assuming the attached turf was non-deformable, hardware/software zeroing prior to loading properly corrects the force plate readings for the raised center of pressure point above the top surface of the force plate.

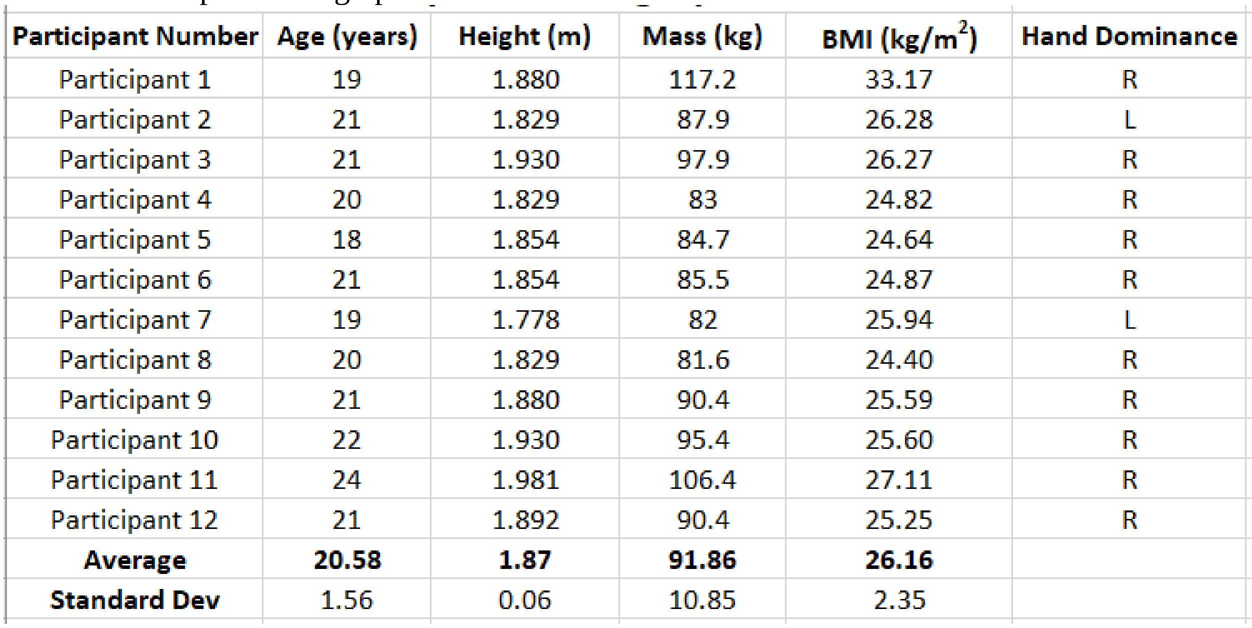
Figure 7. Outdoor laboratory setup. The instrumented pitching mound was setup outside during each day of data collection.

Next, the distance from the front of the pitching rubber to the back point of home plate was measured to be 60 feet 6 inches with an open reel tape measure. A 9-pocket sock net was set up one foot behind the back point of home plate and raised four inches to be used as a target for the pitchers to throw to. Two large sock nets were placed behind the smaller 9-pocket target in order to catch any pitches that missed the target. Equipment used to measure pitch velocity (Rapsodo Pitching 2.0, Rapsodo Pte Ltd., Brentwood, MO) was placed on the ground 15 feet 6 inches from the front of home plate and aimed at the pitcher. A tent was set up behind the instrumented pitching mound with a cart and table to record data. Software (2000Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to process the kinetic data. Two cameras (GoPro Hero 7 Black, GoPro Inc., San Mateo, CA) were utilized to capture video of the participants' pitching motion. One camera was set up 18 inches in front of the edge of the mound on a miniature tripod aimed upward and used to video the frontal plane. The other camera was set up on a large tripod 4 feet high, 4 feet perpendicular from the center of the mound, and used to capture the sagittal plane. All videos were recorded at 60 frames per second at 1080p.

Experimental Procedure

Participants signed all consent forms and the questionnaire prior to data collection and were reminded that they could withdrawal from the study at any time. Height, age, and pitching dominant arm were recorded in the questionnaire (Table 1). Each participants' data were collected in a single throwing session that lasted approximately 60 minutes from warm-up to finish. Each subject wore the team distributed turf shoes (Under Armour Inc., Baltimore MD). Mass was determined via a static trial where the participants stood stationary on the force platform.

Table 1. Participant demographic data



Participant Number	Age (years)	Height (m)	Mass (kg)	BMI (kg/m^2)	Hand Dominance
Participant 1	19	1.880	117.2	33.17	R
Participant 2	21	1.829	87.9	26.28	L
Participant 3	21	1.930	97.9	26.27	R
Participant 4	20	1.829	83	24.82	R
Participant 5	18	1.854	84.7	24.64	R
Participant 6	21	1.854	85.5	24.87	R
Participant 7	19	1.778	82	25.94	L
Participant 8	20	1.829	81.6	24.40	R
Participant 9	21	1.880	90.4	25.59	R
Participant 10	22	1.930	95.4	25.60	R
Participant 11	24	1.981	106.4	27.11	R
Participant 12	21	1.892	90.4	25.25	R
Average	**20.58**	**1.87**	**91.86**	**26.16**	
Standard Dev	1.56	0.06	10.85	2.35	

Participants were given freedom to perform their own warm-up routine and were given as much time as they needed. Participants were instructed to prepare themselves to be able to throw off the mound for at least 15 pitches. After warm-up, each participant was asked to perform one simulated pitching motion in order to analyze their stride length and move the landing force plate, force plate 2 (FP2), into one of the three positions as seen in Figure 8.

Figure 8. Mound framework. The force plate on the flat shelf of the mound where the pitcher's drive leg is located was labeled as FP1, and the force plate on the sloping section where the stride leg lands was labeled as FP2.

Then, participants were asked to place a sleeve containing an inertial measurement unit (IMU) (motusBASEBALL Complete Package, Motus Global Inc., Massapequa, NY), over their throwing elbow so the dot on the motusBASEBALL sleeve was placed over the medial epicondyle and the sensor was approximately two-finger widths distal. The sampling frequency was recorded using the standard software settings of the device at 1000 Hz. Participants were given instruction to throw 15 pitches from the stretch position (Figure 9) at maximum effort: 10 consecutive fastballs followed by 5 breaking balls. All fastball pitches where the subject's foot landed on FP2 were used for the data analysis of this study. No experience of pain was reported by any participants.

Figure 9. Stretch position. The pitcher is shown in the set position with his drive leg foot touching the front of the pitching rubber just before leg lift of the stride leg.

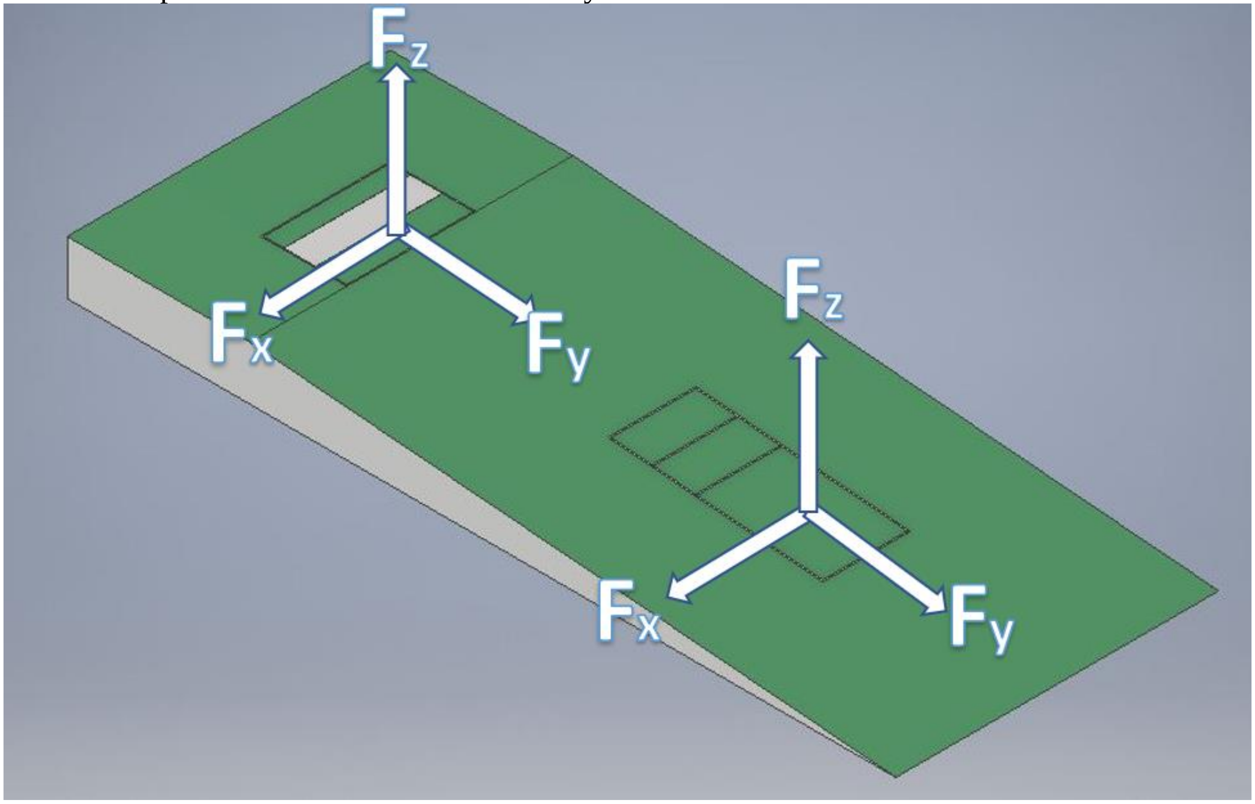
Ground Reaction Forces

Ground reaction forces were recorded in all three directions at a sampling frequency of 2000 Hz. The x-direction was defined as toward 3rd base (transverse plane). The y-direction was defined as towards home plate (frontal plane). The z-direction was defined as the vertical force upward (transverse plane). Both force plates were calibrated to match this coordinate system. The impulse of the drive leg was defined as the area under the curve from leg lift until zero force for the drive leg in the y-direction. The peak braking force was defined as the maximum amplitude of force from the stride leg in the negative y-direction.

Description of Biomechanical Measures

The three-dimensional coordinate system is shown in Figure 10. The direction from the pitcher's mound to home plate was defined as the positive Y-direction and in the direction of the pitch. This direction is referenced as the anterior-posterior direction due to the general reference of the body in relation to the pitch. The drive leg produced forces toward 2nd base and in the opposite direction of the pitch while the stride leg produced forces towards home plate. This study focuses primarily on forces in the anterior-posterior direction.

Figure 10. Coordinate System of the Force Plate. The CAD design of the instrumented pitching mound is depicted with the local coordinate system orientations.

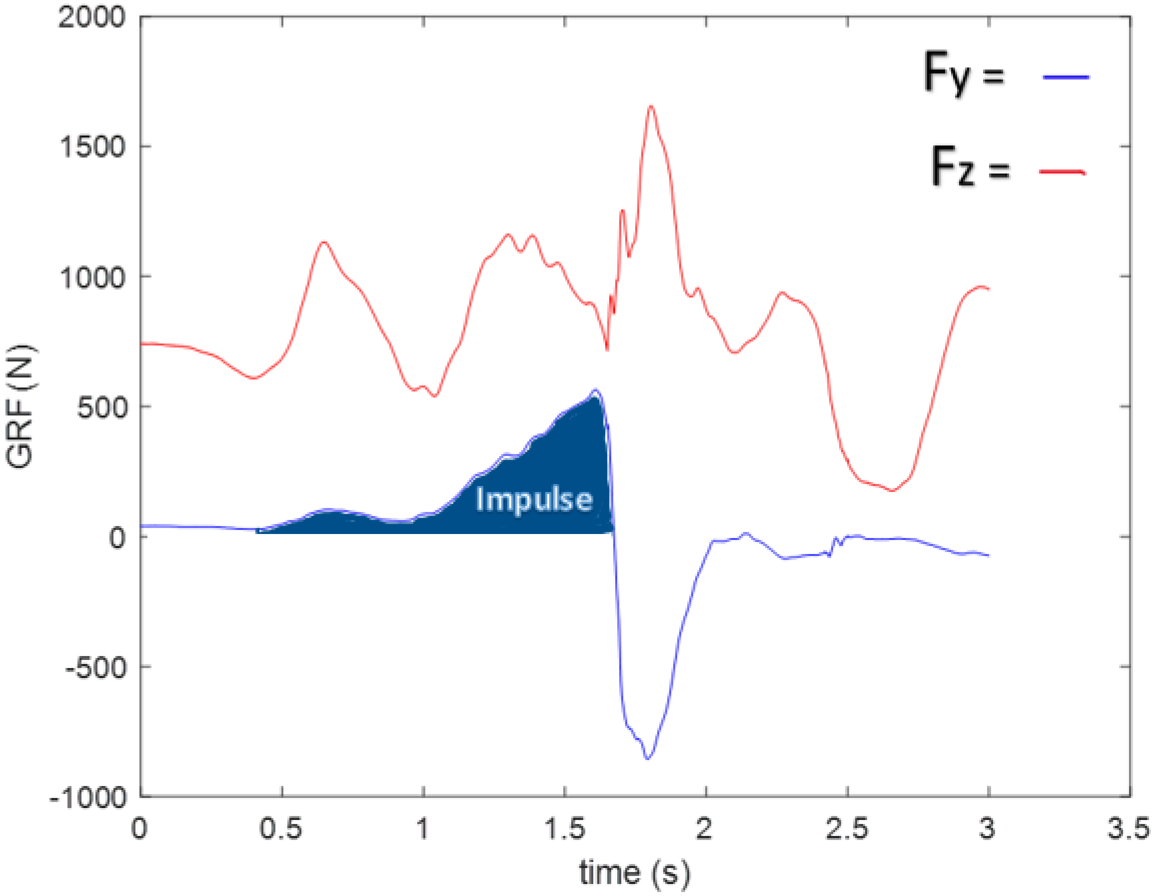


The direction from the pitcher’s mound to 3rd base was defined as the positive X-direction and referred to as the medial-lateral direction. Most of the forces produced in this direction were from the rotation of the pitching motion. The forces in this plane of direction were minimal as most of the forces produced were in the direction plane of the pitch or in the vertical direction.

The direction from the pitcher’s mound towards the sky was defined as the positive Z-direction. Most of the force in this direction is from the weight of the participants. Forces produced by the stride leg were greater due to the elevation of the mound. Forces from the drive leg during the stride phase in this direction were slightly more than body weight while forces produced from the stride leg during the landing phase were more than 1.5 times body weight.

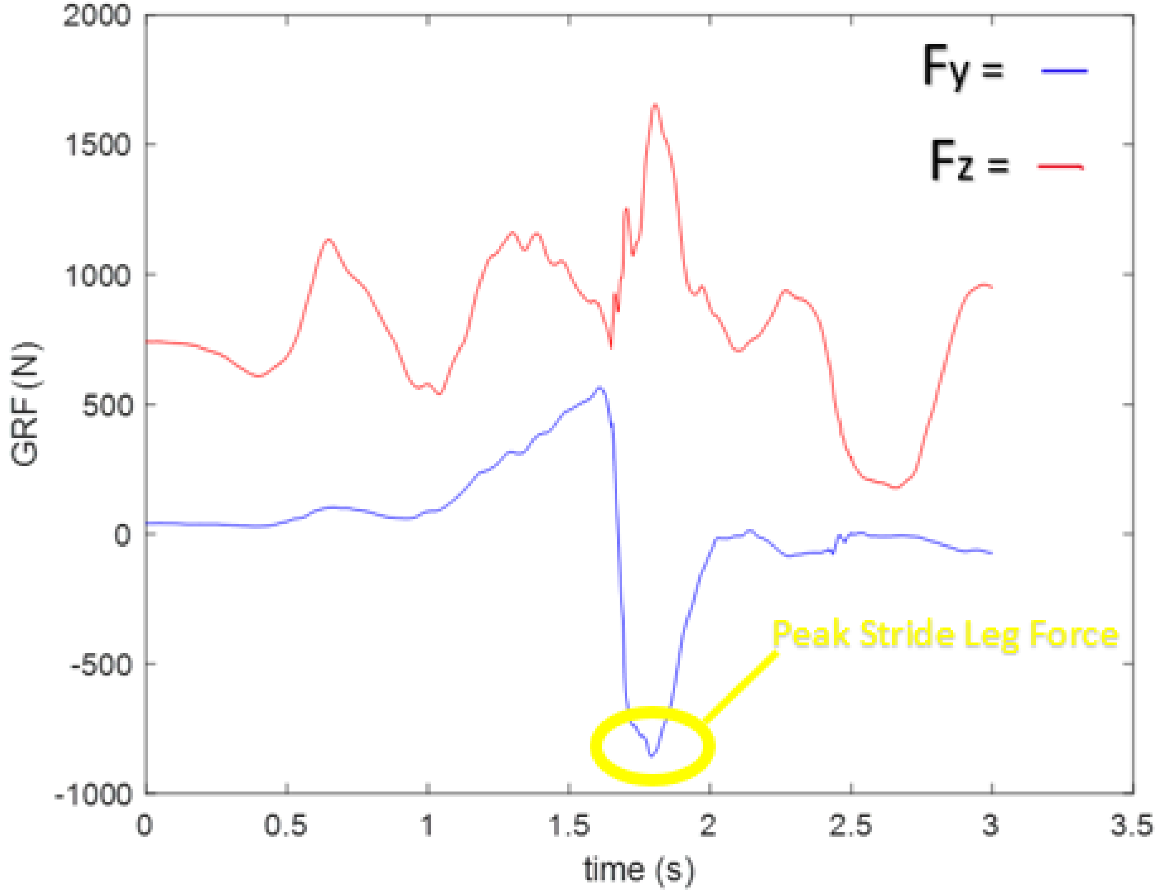
Impulse of the drive leg is defined as the cumulative amount of force over time the pitcher produces in the anterior-posterior direction from the time when the pitcher lifts the stride leg and moves down the mound until the Fy curve reaches zero and begins to move in the negative direction. This kinetic variable of impulse is the area under the curve in the anterior-posterior direction between these two temporal parameters and is also known as the integral of the Fy curve (Figure 11).

Figure 11. Force Versus Time Curve Depicting Impulse. Impulse of the drive leg is depicted as the area under the Fy curve shown by the region shaded in blue.



Peak ground reaction force of the stride leg is defined as the maximum amplitude of the stride leg produced after foot strike in the anterior-posterior direction (Figure 12). This is the force that stops the forward momentum produced from the drive leg and transfers the energy from the stride foot up the kinetic chain.

Figure 12. Force Versus Time Curve Depicting Peak Stride Leg Force. Peak stride leg force in the anterior-posterior direction is depicted within the yellow highlighted circle.



Elbow varus torque was defined as the reading given by the motusBASEBALL sleeve of the maximum elbow varus torque during the arm cocking phase when the arm is near maximum external rotation. Studies have been used to investigate the accuracy of more accessible technologies such as the motusBASEBALL sleeve (motusBASEBALL Complete Package, Motus Global Inc., Massapequa, NY). Wight et al. found that all motusBaseball sleeve kinetic measurements held a significant level of reliability and accuracy when compared to marker-based motion capture kinetics [24]. Elbow varus torque is a prominent measure used to investigate relationships to injury. This parameter was measured in newton*meters.

Pitch velocity was defined as the reading given by the Rapsodo Pitching 2.0 unit. This parameter is one of the primary measures used to assess the performance of pitchers and was measured in miles per hour.

Data Analysis

The group means and standard deviations were calculated for all variables. All kinetic data points were normalized to body weight. Excel (Microsoft Corporation, Redmond, WA) was used to determine significant correlations between variables. Pearson product-moment correlations were performed for each research question; the correlation coefficient (r) and p-values were reported for each. The correlation coefficient was the primary metric used to measure correlations and represents how strong the linear relationship is. The a priori alpha level was set to 0.05. Kurtosis and skewness values were calculated and recorded between -1 and 1 to ensure normal distribution of data. Correlations between ground reaction forces, pitch velocity, and elbow varus torque were investigated. All available trials were used. Code written in Matlab (The Mathworks, Natick, MA) was created to display graphs of the ground reaction forces in vertical and AP directions. Additional code was implemented to calculate the peak stride leg ground reaction force and impulse of the drive leg. Elbow varus torque, arm slot, arm speed, and shoulder rotation velocity were all exported from the Motus Sleeve; however, elbow varus torque was the only variable used in this study.

CHAPTER III

RESULTS

Several ground reaction kinetic variables were correlated to increased pitch velocity and decreased elbow varus torque. For the drive leg, impulse in the AP direction was significantly related to pitch velocity (p-value < 0.001, r = 0.366) (Figure 13). Additionally, impulse in the AP direction was inversely related to elbow varus torque (p-value = 0.001, r = -0.299) (Figure 14). For the stride leg, peak force in the AP direction was significantly related to pitch velocity (p-value = 0.013, r = 0.222) (Figure 15). Linear regression statistics are shown in Table 2, and the number of observations is lower in the correlation relating impulse to elbow torque due to a few trials that did not get a reading of elbow torque from the Motus Sleeve. The results in Table 3 show that impulse correlates to pitch velocity the greatest and secondly correlates to elbow varus torque. The standard deviations for pitch velocity in Table 3 are very small and do not exceed 1.70 miles per hour. Participant 2 had the lowest impulse, but greatest elbow varus torque as shown in Table 3.

Figure 13. Impulse of Drive leg vs Velocity. Data from all participants and all available trials are shown.

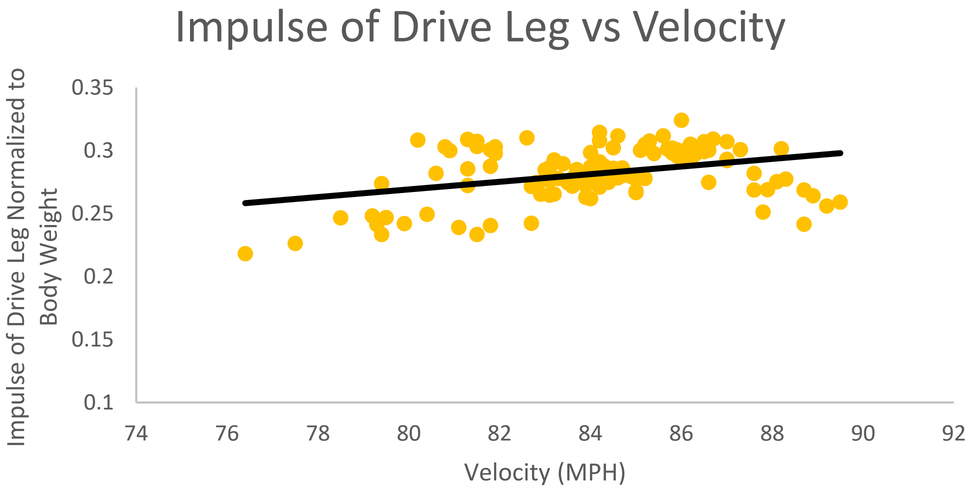


Figure 14. Impulse of Drive Leg vs Elbow Varus Torque. Data from all participants and all available trials are shown.

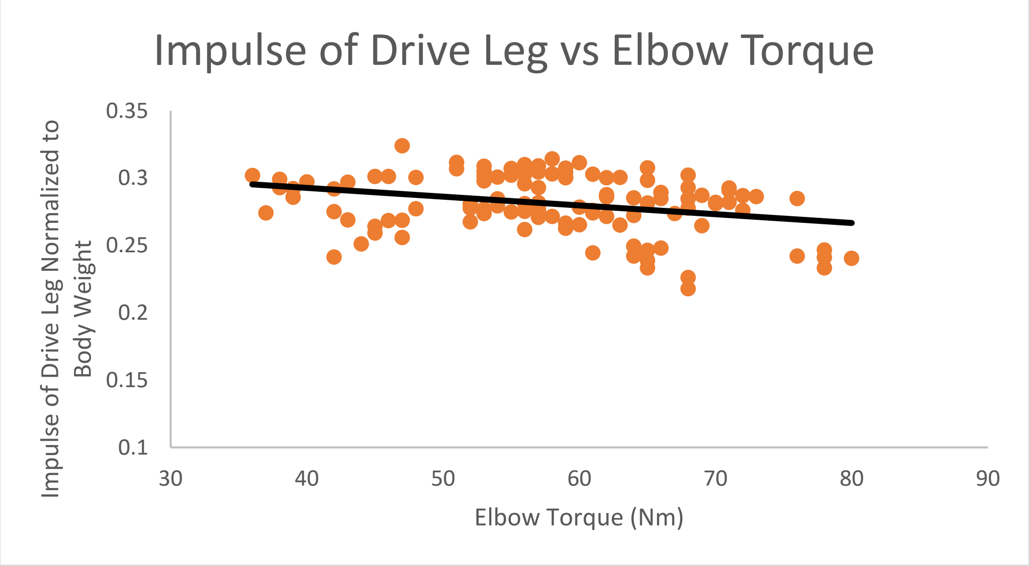


Figure 15. Peak Force of the Stride Leg in the Anterior-Posterior Direction vs Pitch Velocity. Data from all participants and all available trials are shown.

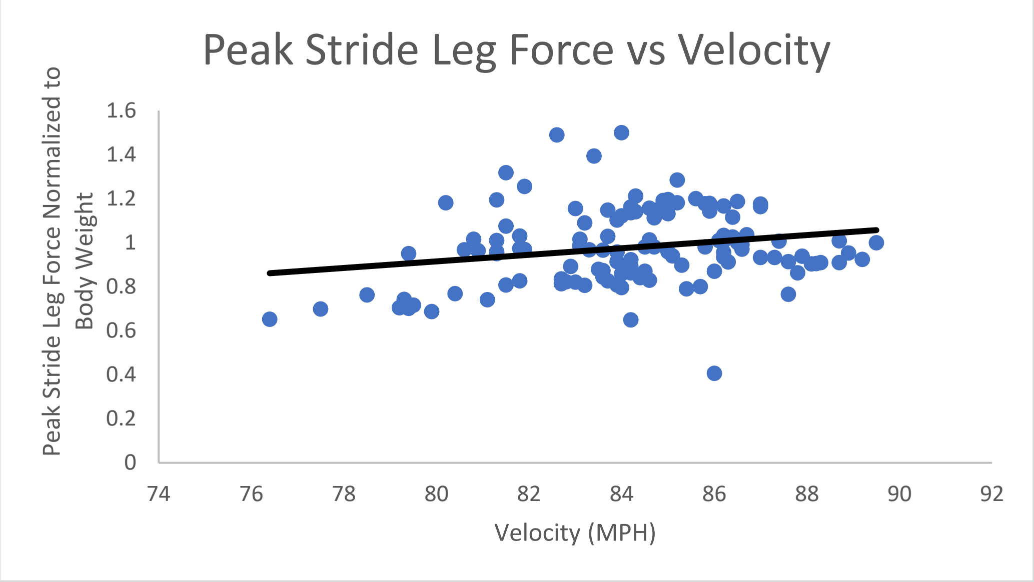


Table 2. Linear Regression Statistics. Regression statistics of biomechanical measures and their correlations.

Regression Statistics			
	Peak Stride Leg Force vs Velocity	**Impulse vs Velocity**	**Impulse vs Elbow Torque**
Multiple R	0.222	0.366	0.299
R Square	0.049	0.134	0.089
Observations	124	123	117
Significance	0.013	< 0.001	0.001

Table 3. Means and standard deviations of drive leg impulse and peak stride leg force normalized to body weight in relation to pitch velocity and elbow varus torque for all participants.

	Peak Stride Leg Force vs Velocity		Drive Leg Impulse vs Velocity		Drive Leg Impulse vs Elbow Varus Torque	
Participant Number	**Peak Stride Leg Force**	**Velocity (mph)**	**Impulse**	**Velocity (mph)**	**Impulse**	**Elbow Varus Torque (N*m)**
Participant 1	0.922 ± 0.056	87.95 ± 1.07	0.276 ± 0.023	87.99 ± 1.10	0.276 ± 0.023	45.36 ± 2.02
Participant 2	0.738 ± 0.052	79.75 ± 1.69	0.239 ± 0.009	79.75 ± 1.69	0.239 ± 0.009	69.71 ± 6.67
Participant 3	0.952 ± 0.056	85.88 ± 0.93	0.293 ± 0.008	85.88 ± 0.93	0.293 ± 0.008	39.11 ± 2.26
Participant 4	1.169 ± 0.024	86.15 ± 0.59	0.302 ± 0.006	86.15 ± 0.59	0.302 ± 0.006	54.00 ± 2.21
Participant 5	0.881 ± 0.141	84.29 ± 0.64	0.305 ± 0.008	84.29 ± 0.64	0.305 ± 0.008	63.71 ± 4.89
Participant 6	0.889 ± 0.193	86.27 ± 0.70	0.296 ± 0.011	86.27 ± 0.70	0.296 ± 0.011	60.11 ± 3.92
Participant 7	1.203 ± 0.135	84.08 ± 0.56	0.285 ± 0.004	84.08 ± 0.56	0.285 ± 0.004	67.80 ± 5.49
Participant 8	1.142 ± 0.178	81.39 ± 0.67	0.305 ± 0.004	81.39 ± 0.67	0.306 ± 0.003	56.43 ± 2.51
Participant 9	0.934 ± 0.054	83.97 ± 0.67	0.274 ± 0.006	83.97 ± 0.67	0.274 ± 0.006	61.44 ± 1.51
Participant 10	1.160 ± 0.063	84.39 ± 1.02	0.280 ± 0.009	84.39 ± 1.02	0.280 ± 0.009	53.70 ± 2.26
Participant 11	0.835 ± 0.023	83.55 ± 0.60	0.271 ± 0.006	83.55 ± 0.60	0.270 ± 0.006	57.22 ± 1.56
Participant 12	0.983 ± 0.027	82.07 ± 1.41	0.279 ± 0.007	82.07 ± 1.41	0.280 ± 0.007	68.67 ± 2.83

CHAPTER IV

DISCUSSION

During the pitching motion, force is transferred from the ground up the kinetic chain from the lower extremity to the trunk, and finally to the upper extremity, up to the hand and ball. Creating efficient movements helps maximize the amount of force produced and maximize the transfer of energy throughout each segment of the chain to achieve maximum pitch velocity. The purpose of this study was to determine if correlations exist between impulse or peak ground reaction forces and pitch velocity and elbow torque. Obtaining a better understanding of lower extremity pitching mechanics may lead to more efficient movements further up the chain to decrease elbow torque and reduce the risk of elbow injuries in pitchers.

Impulse of the drive leg in the anterior-posterior direction was chosen as the primary metric to analyze due to the crucial role the drive leg plays in generating the initial momentum to start the sequence of movements of the kinetic chain. It was hypothesized that impulse of the drive leg in the anterior-posterior direction would correlate with increased pitch velocity. This hypothesis was supported as the results of this study concluded that the impulse of the drive leg in the anterior-posterior direction was significantly related to pitch velocity. These results are supported by previous similar studies that showed impulse ground reaction force of the drive leg correlated with energy flow to segments of the upper extremity [20]. Howenstein et al. found the impulse of the drive leg related to energy flow into segments of the upper extremity in youth baseball pitchers [20]. The impulse of the drive leg occurs towards the beginning of the sequence of events within the kinetic chain during a pitch. This study did not analyze energy flow of various segments of the kinetic chain but instead focused on the initial portion of the kinetic chain, impulse of the drive leg, and the last portion of the kinetic chain, the pitch velocity. If a greater impulse is achieved, but the subsequent events after impulse did not effectively transfer the energy, then the energy lost would result in a lower pitch velocity.

It was hypothesized that impulse of the drive leg in the anterior-posterior direction would correlate with decreased elbow varus torque. This hypothesis was supported as an increase in impulse of the drive leg in the anterior-posterior direction had an inverse correlation to elbow varus torque. This result is similar to findings of Kibler that found a 20 percent decrease in kinetic energy delivered from the hip and trunk to the arm requires a 34 percent increase in the rotational velocity of the shoulder to impart the same amount of force to the hand [25]. This is likely due to transferring the energy from larger segments of the kinetic chain up to the smaller segments of the kinetic chain in the upper extremity and reducing the required amount of force to be generated by joints in the smaller upper extremity. However, if disconnects or inefficient movements exist between the impulse of the drive leg and the time of maximum elbow varus torque, then the results might be negatively affected. The current study found impulse of the drive leg is correlated with decreased elbow torque. Mayberry et al. discovered that pitchers who rely too much or too little on impulse momentum may place more stress on distal joints such as the elbow. This finding is similar to the results of this study as the pitchers who generated greater impulse with the drive leg were found to have less elbow varus torque. However, the findings from this study do not show any indication that too much impulse from the drive leg relates to an increase in elbow varus torque.

It was hypothesized that the peak stride leg ground reaction force would correlate with increased pitch velocity. The results from this study support the hypothesis as this study concluded peak stride leg ground reaction force in the anterior-posterior direction was related to increased pitch velocity. This result is similar to Kageyama et al. that found maximum stride leg ground reaction force was significantly greater in a high-ball-velocity group versus a low-ball velocity group [12]. The result from this current study also supports previous studies that found peak stride leg ground reaction force correlated to increased pitch velocity [2], [18], [19]. This is also in line with the study by Howenstein et al. that found peak stride leg braking force related to increased energy flow into distal segments of the upper extremity [20]. This current study did not find as strong of a correlation as most previous studies which could be from this study having a smaller number of participants. In addition, one of the pitchers used for analysis in this study was a side arm pitcher that may not rely as much on ground reaction forces. The peak stride leg force occurs during the arm acceleration phase just before or at ball release and is at the end of the kinetic chain. If the energy is transferred effectively throughout the chain, this is the last kinetic variable before ball release. If the stride leg is effectively used to brake the forward momentum and produce a greater peak force, it is much more likely for the results to be directly correlated to pitch velocity. The drive leg produces force into the ground to propel the body forward and then as the stride leg plants into the ground to brake this forward momentum, energy is transferred from the ground up the kinetic chain to the hand and ball similar to the motion of a whip. The stride leg force acts as a counter force to those produced by the drive leg and they work together to maintain the flow of energy throughout the kinetic chain to generate energy to the ball.

Delimitations

Several delimitations and boundaries were set for this study that should be noted. All subjects were healthy and had no history of surgery in the past 12 months. Additionally, all subjects wore the same team issued turf shoe to reduce any differences in dampening of the ground reaction forces. Furthermore, all subjects were familiar with throwing on an artificial turf mound.

Limitations

There are several limitations that should be considered from this study. Only twelve participants were recruited for this study, and the limited number of data may skew results. Additionally, the surface of the mound was layered with artificial turf, and turf shoes were worn that may not have provided the same traction as cleats that sink into the ground more. Due to COVID-19 and social distancing policies, we were not able to use kinematic markers to determine elbow or shoulder kinetics. Although the motusBASEBALL sleeve has been verified to produce similar kinetics to those from motion capture systems, the sleeve was looser on some participants and tended to slide down the arm and need readjusting more for some participants than others. Finally, participants were not given a standardized warm-up.

Summary

The results of this study show how ground reaction forces relate to loads on the elbow and pitch velocity. Increasing the impulse on the drive leg may lead to greater pitch velocity and a decrease in elbow varus torque. Additionally, increasing stride leg peak ground reaction forces may lead to greater pitch velocity. Understanding these factors may lead to increases in pitch velocity and decrease elbow varus torque. This study focuses on how pitchers produce force leading up to ball release to maximize pitch velocity; however, a better understanding of forces after ball release may give more insight as to how these forces are optimally dissipated and how they are related to injury. These findings may have an impact on other overhead throwing athletes such as football quarterbacks and javelin throwers. Future studies should be conducted to analyze the primary musculature that is activated to help produce these forces, and this could help impact strength training techniques.

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APPENDIX A

CONSENT FORM

INFORMED CONSENT DOCUMENT
OLD DOMINION UNIVERSITY

PROJECT TITLE: Ground Reaction Forces Relationship to Medial Elbow Stress and Implications for Injury in Collegiate Baseball Pitchers

INTRODUCTION

The purposes of this form are to give you information that may affect your decision whether to say YES or NO to participation in this research, and to record the consent of those who say YES.

The research on Ground Reaction Forces Relationship to Medial Elbow Stress and Implications for Injury in Collegiate Baseball Pitchers will be conducted at the Bud Metheny Baseball Complex.

RESEARCHERS

Dr.Stacie Ringleb, a faculty member from Old Dominion University Batten College of Engineering and Technology in the department of Mechanical and Aerospace Engineering, is the principal investigator for this research.
Dr. Hunter Bennett, a faculty member from Old Dominion University Darden College of Education and Professional Studies in the department of Human Movement Sciences, is an investigator for this research
Brett Smith, a graduate student from Old Dominion University Batten College of Engineering and Technology in the department of Biomedical Engineering, is an investigator for this research.

DESCRIPTION OF RESEARCH STUDY

Several studies have been conducted looking into the subject of forces produced from pitchers' feet and indicators for injury in baseball pitchers. None of them have explained the effects of forces produced from pitchers' feet on the corresponding loads placed on the elbow.

If you decide to participate, then you will join a study involving research of pitching biomechanics and the relationship between forces produced from pitchers' feet and stress placed on the elbow. You are expected to throw 20 pitches on a pitching mound built with two force plates embedded under the stride and landing foot. Subjects will throw 20 fastballs off of a mound and into a net while wearing the Motus sleeve (a compression sleeve with a small sensor embedded) on their throwing arm. If you say YES, then your participation will last for approximately one hour and 30 minutes at the Bud Metheny Baseball Complex. Approximately 25 collegiate baseball pitchers will be participating in this study.

EXCLUSIONARY CRITERIA

You should have completed the medical history questionnaire. To the best of your knowledge, you should not have recent injury to any lower or upper extremity in the previous 3 months that impairs movement and joint function or have a history of surgery in the past 12 months that would keep you from participating in this study. Additionally, you should not participate in this study if you fall outside of the age range of 18-30 and you are not a collegiate baseball pitcher.

.

RISKS AND BENEFITS

RISKS: If you decide to participate in this study, then you may face a risk of physical harm or release of confidential information. The researcher tried to reduce these risks by always having an investigator present and nearby the participants as well as keeping all data and information stored in a locked cabinet file or password protected computer. Additionally, if you give consent for photo and video to be taken during this study you may face a risk of anonymity and confidentiality. The researcher has tried to reduce this risk by keeping all video on a micro SD card that only the researcher has access to, deleting video after the completion of the study, and only using photos or videos for professional presentations or publications.

And, as with any research, there is some possibility that you may be subject to risks that have not yet been identified.

BENEFITS: There are no direct benefits to you for participating in the study. The proposed study has potential benefits to produce data that will help baseball pitchers better understand the kinetic chain and provide valuable information to help reduce the high rates of injuries in pitchers. The potential benefits could be significant enough to generate valuable data in reducing the risk of injury in ptichers across the world, and only present a potential minimal risk on a small number of subjects.

COSTS AND PAYMENTS

The researchers want your decision about participating in this study to be absolutely voluntary. Yet they recognize that your participation may pose some inconvenience, however, the researchers are unable to give you any payment for participating in this study.

NEW INFORMATION

If the researchers find new information during this study that would reasonably change your decision about participating, then they will give it to you.

CONFIDENTIALITY

The researchers will take reasonable steps to keep private information, such as questionnaires and medical history, confidential. The researcher will remove identifiers from all identifiable private information collected. Your data will be recorded based on a number/code assigned to you. This number assigned will be used as your subject ID when collecting and storing data within the Motus application. The questionnaires given to you will be anonymous and you will be asked to NOT write your name on the questionnaire. All data will be coded in order to protect your confidentiality. Only the researchers will have access to the coding. Your information will be kept within a locked file cabinet. Upon completion of the study, coding material will be destroyed removing any possible link between the data and identifiers. Any computers used to capture data will be password protected and data files will be labeled only using the participant code. Your information will not be used or distributed for future research studies even if identifiers are removed. All video will be stored on a micro SD card that only the investigators will have access to until the completion of this study. All video will be deleted after completion of the study except for video being used only for professional presentations or publications. The results of this study may be used in reports, presentations, and publications; but the researcher will not identify you. Of course, your records may be subpoenaed by court order or inspected by government bodies with oversight authority.

WITHDRAWAL PRIVILEGE

It is OK for you to say NO. Even if you say YES now, you are free to say NO later, and walk away or withdraw from the study -- at any time. Your decision will not affect your relationship with Old Dominion University, or otherwise cause a loss of benefits to which you might otherwise be entitled.

COMPENSATION FOR ILLNESS AND INJURY

If you say YES, then your consent in this document does not waive any of your legal rights. However, in the event of injury arising from this study, neither Old Dominion University nor the researchers are able to give you any money, insurance coverage, free medical care, or any other compensation for such injury. In the event that you suffer injury as a result of participation in any research project, you may contact the responsible principal investigator, Dr. Stacie Ringleb at 757-683-5934 or investigators at the following phone numbers; Dr. Hunter Bennett at 757-683-4387, Brett Smith at 757-633-0447, Dr. Tancy Vandecar-Burdin the current IRB chair at 757-683-3802 at Old Dominion University, or the Old Dominion University Office of Research at 757-683-3460 who will be glad to review the matter with you.

VOLUNTARY CONSENT

By signing this form, you are saying several things. You are saying that you have read this form or have had it read to you, that you are satisfied that you understand this form, the research study, and its risks and

benefits. The researchers should have answered any questions you may have had about the research. If you have any questions later on, then the researchers should be able to answer them:
Dr. Stacie Ringleb: 757-683-5934
Brett Smith: 757-633-0447
Dr. Hunter Bennett: 757-683-4387,

If at any time you feel pressured to participate, or if you have any questions about your rights or this form, then you should call Dr. Tancy Vandecar-Burdin, the current IRB chair, at 757-683-3802, or the Old Dominion University Office of Research, at 757-683-3460.

And importantly, by signing below, you are telling the researcher YES, that you agree to participate in this study. The researcher should give you a copy of this form for your records.

Subject's Printed Name & Signature	**Date**

INVESTIGATOR'S STATEMENT

I certify that I have explained to this subject the nature and purpose of this research, including benefits, risks, costs, and any experimental procedures. I have described the rights and protections afforded to human subjects and have done nothing to pressure, coerce, or falsely entice this subject into participating. I am aware of my obligations under state and federal laws, and promise compliance. I have answered the subject's questions and have encouraged him/her to ask additional questions at any time during the course of this study. I have witnessed the above signature(s) on this consent form.

Investigator's Printed Name & Signature	**Date**

APPENDIX B

PHOTO – VIDEO CONSENT FORM

INFORMED CONSENT DOCUMENT FOR USE OF PHOTO/VIDEO MATERIALS

STUDY TITLE: Ground Reaction Forces Relationship to Medial Elbow Stress and Implications for Injury in Collegiate Baseball Pitchers

DESCRIPTION:

The researchers would also like to take photographs or videotapes of you pitching in order to illustrate the research in teaching, presentations, and/or or publications.

CONFIDENTIALITY:

All video will be stored on a micro SD card that only the investigators will have access to until the completion of this study. All video will be deleted after completion of the study except for video being used only for professional presentations or publications. You would not be identified by name in any use of the photographs or videotapes. Even if you agree to be in the study, no photographs or videotapes will be taken of you unless you specifically agree to this.

VOLUNTARY CONSENT

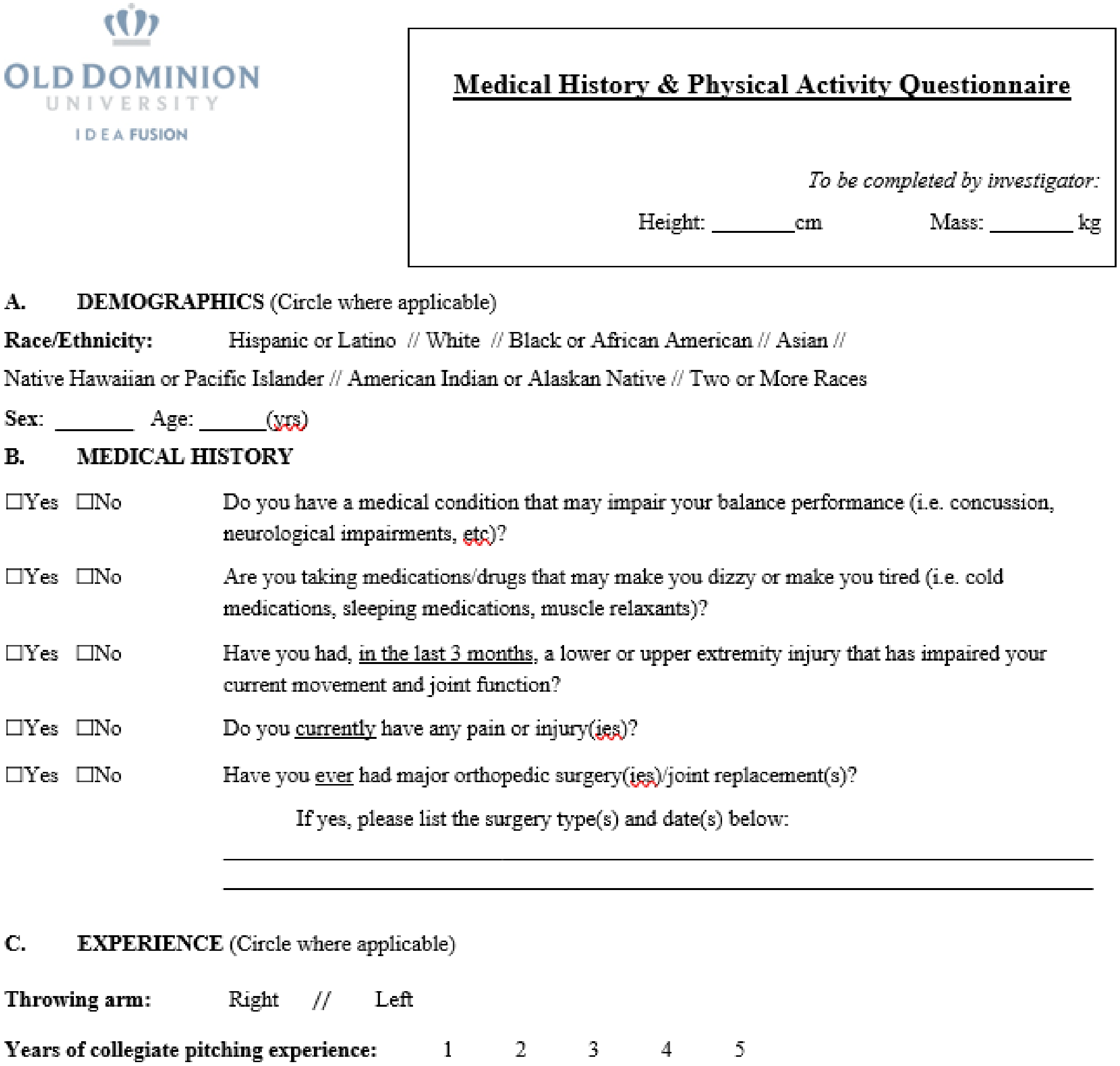
By signing below, you are granting to the researchers the right to use your likeness, image, appearance and performance - whether recorded on or transferred to videotape, film, slides, photographs - for presenting or publishing this research. No use of photos or video images will be made other than for professional presentations or publications. The researchers are unable to provide any monetary compensation for use of these materials. You can withdraw your voluntary consent at any time.

If you have any questions later on, then the researchers should be able to answer them:
Dr. Stacie Ringleb: 757-683-5934
Brett Smith: 757-633-0447
Dr. Hunter Bennett: 757-683-4387
If at any time you feel pressured to participate, or if you have any questions about your rights or this form, then you should call Dr. Tancy Vandecar-Burdin, the current IRB chair, at 757-683-3802, or the Old Dominion University Office of Research, at 757-683-3460.

Subject's Printed Name & Signature	**Date**
Parent / Legally Authorized Representative's Printed Name & Signature (If applicable)	**Date**
Witness' Printed Name & Signature (if Applicable)	**Date**

APPENDIX C

QUESTIONNAIRE



OLD DOMINION UNIVERSITY
IDEA FUSION

Medical History & Physical Activity Questionnaire

To be completed by investigator:

Height: _______cm Mass: _______ kg

A. DEMOGRAPHICS (Circle where applicable)

Race/Ethnicity: Hispanic or Latino // White // Black or African American // Asian // Native Hawaiian or Pacific Islander // American Indian or Alaskan Native // Two or More Races

Sex: _______ Age: ______(yrs)

B. MEDICAL HISTORY

☐Yes ☐No Do you have a medical condition that may impair your balance performance (i.e. concussion, neurological impairments, etc)?

☐Yes ☐No Are you taking medications/drugs that may make you dizzy or make you tired (i.e. cold medications, sleeping medications, muscle relaxants)?

☐Yes ☐No Have you had, in the last 3 months, a lower or upper extremity injury that has impaired your current movement and joint function?

☐Yes ☐No Do you currently have any pain or injury(ies)?

☐Yes ☐No Have you ever had major orthopedic surgery(ies)/joint replacement(s)?

If yes, please list the surgery type(s) and date(s) below:

____

____

C. EXPERIENCE (Circle where applicable)

Throwing arm: Right // Left

Years of collegiate pitching experience: 1 2 3 4 5

APPENDIX D

MATLAB CODE FOR FORCE-TIME CURVE AND PEAK STRIDE LEG FORCE

```
Clear

clc

% Create empty matrix for Impulse Variable for all %%%% 1 %%%% subjects
Impulse_matrix = nan(1,1);   % number of subjects is the first variable, number of
trials is the second

% All excel files should have the same naming scheme
pathname = 'C:/DATA_COLLECTION/Subject2/'; %%%%% make sure the pathname matches the
location of the actual files
Subjects = {'S2_Fast_'};
Trials = {'T5'};
filename = '.csv';

a=6;
b=13100;
BW = 1149;
% Iterate subjects (i) trials (j)
for i=[1]
    for j=[1]   % only look at 1 subject and 1 trial for now
    % Import file
    file = [pathname Subjects{i} Trials{j} filename];

    clear numData FP1_ML_GRF FP1_AP_GRF FP1_V_GRF FP2_ML_GRF FP2_AP_GRF FP2_V_GRF FP1
FP2 ML_GRF_Total AP_GRF_Total V_GRF_Total

    numData = dlmread (file,',',a,0); % can change the 10000 to any number in order to
avoid headers

    [r,c] = size(numData);

    time = (0.001:0.001:r*0.001)';

   FP1_ML_GRF = (numData(:,3)).*-1;
    FP1_AP_GRF = (numData(:,4)).*-1;
    FP1_V_GRF = (numData(:,5)).*-1;
    FP2_ML_GRF = (numData(:,12)).*-1;
    FP2_AP_GRF = (numData(:,13)).*-1;
    FP2_V_GRF = (numData(:,14)).*-1;
```

```
FP1 = [FP1_ML_GRF FP1_AP_GRF FP1_V_GRF];
FP2 = [FP2_ML_GRF FP2_AP_GRF FP2_V_GRF];

ML_GRF_Total = (FP1_ML_GRF + FP2_ML_GRF);
AP_GRF_Total = (FP1_AP_GRF + FP2_AP_GRF);
V_GRF_Total = (FP1_V_GRF + FP2_V_GRF);

% plots to visualize GRFs
figure(1)
subplot(3,1,1)
plot(time,FP1_ML_GRF,'b')
title('FP1 ML GRF')
xlabel('time (s)')
ylabel('GRF (N)')
hold on
subplot(3,1,2)
plot(time,FP2_ML_GRF,'r')
title('FP2 ML GRF')
xlabel('time (s)')
ylabel('GRF (N)')
hold on
subplot(3,1,3)
plot(time,ML_GRF_Total,'k')
title('ML GRF Total')
xlabel('time (s)')
ylabel('GRF (N)')
hold on

figure(2)
subplot(3,1,1)
plot(time,FP1_AP_GRF,'b')
title('FP1 AP GRF')
xlabel('time (s)')
ylabel('GRF (N)')
hold on

subplot(3,1,2)
plot(time,FP2_AP_GRF,'r')


%find peak stride leg GRF
[M,I] = min(FP2_AP_GRF)

title('FP2 AP GRF')
xlabel('time (s)')
ylabel('GRF (N)')
hold on
subplot(3,1,3)
plot(time,AP_GRF_Total,'k')
title('AP GRF Total')
```

```
    xlabel('time (s)')
    ylabel('GRF (N)')
    hold on


    figure(3)
    subplot(3,1,1)
    plot(time,FP1_V_GRF,'b')
    title('FP1 V GRF')
    xlabel('time (s)')
    ylabel('GRF (N)')
    hold on
    subplot(3,1,2)
    plot(time,FP2_V_GRF,'r')
    title('FP2 V GRF')
    xlabel('time (s)')
    ylabel('GRF (N)')
    hold on
    subplot(3,1,3)
    plot(time,V_GRF_Total,'k')
    title('V GRF Total')
    xlabel('time (s)')
    ylabel('GRF (N)')
    hold on

    figure(4)
    hold on
    plot(time,AP_GRF_Total,'b')
    hold on
    plot(time,V_GRF_Total,'r')
    hold on


    end
end
```

APPENDIX E

MATLAB CODE FOR IMPULSE CALCULATIONS

```
clear

clc



% Create empty matrix for Impulse Variable for all %%%% 1 %%%% subjects
Impulse_matrix = nan(1,1);   % number of subjects is the first variable, number of
trials is the second


% All excel files should have the same naming scheme
pathname = 'C:/DATA_COLLECTION/Subject5/'; %%%%% make sure the pathname matches the
location of the actual files
Subjects = {'S5_Fast_'};
Trials = {'T10'};
filename = '.csv';


a=6416; % start point to begin calculating the integral or impulse
b=8865; % end point to terminate calculating the integral or impulse
for i=[1]
    for j=[1]


     file = [pathname Subjects{i} Trials{j} filename];


    clear numData FP1_ML_GRF FP1_AP_GRF FP1_V_GRF FP2_ML_GRF FP2_AP_GRF FP2_V_GRF FP1
FP2 ML_GRF_Total AP_GRF_Total V_GRF_Total

    numData = dlmread (file,',',[a,0,b,19]); % can change to any number in order to
avoid headers

    [r,c] = size(numData);

     time = (0.0005:0.0005:r*0.0005)';

     FP1_AP_GRF = (numData(:,4)).*-1;         %gives force in newtons
```

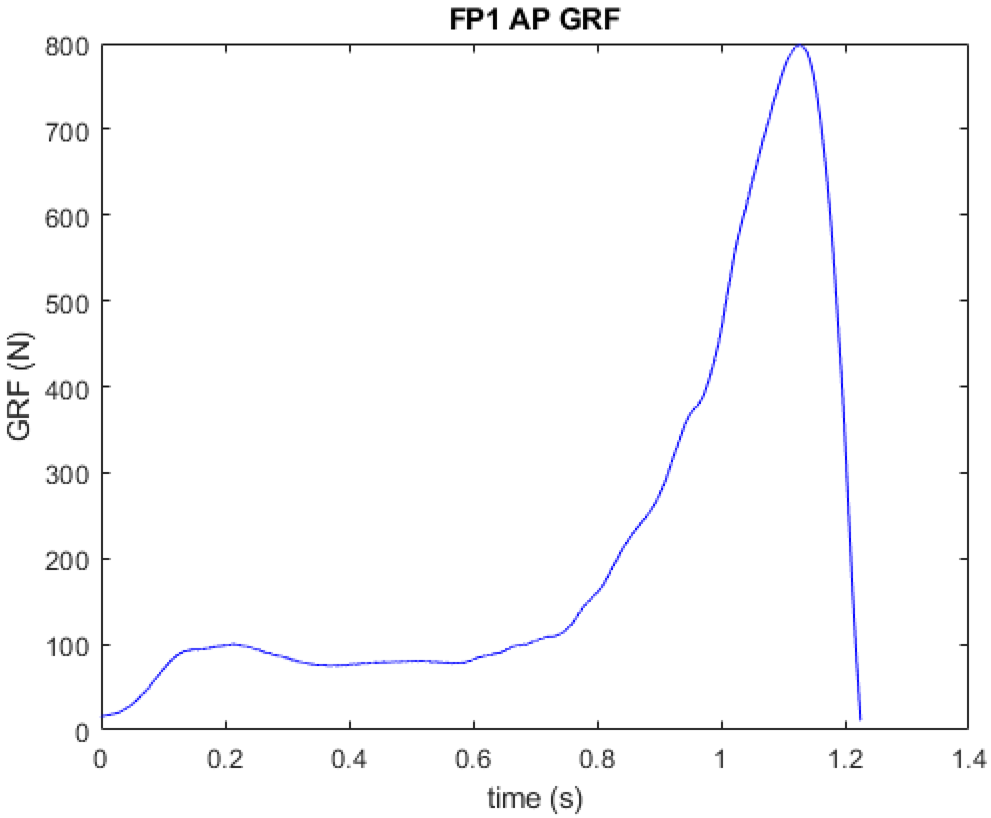
```
    figure(1)
    plot(time,FP1_AP_GRF,'b')
    title('FP1 AP GRF')
    xlabel('time (s)')
    ylabel('GRF (N)')
    hold on

     Impulse_Back_FP1_AP = trapz(time,FP1_AP_GRF)

    end
end
```

```
Impulse_Back_FP1_AP =

  261.2405
```



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VITA

Brett Smith was born and raised in Chesapeake, VA and graduated from Grassfield High School in 2019. While in high school, he started a business called Birdhouses for Homeless to sell birdhouses and use profits to provide food for the homeless during the winter months. After high school, Brett attended Old Dominion University where he earned a Bachelor of Science in Mechanical Engineering in 2019 and played baseball for the University all four years.

While at Old Dominion, Brett worked as a graduate assistant for the Engineering Dean's Office where he assisted the Deans of Research to help organize and analyze data for research and participated in departmental and research advisory meetings. While he worked to earn his graduate degree in Biomedical Engineering, he also continued his baseball career with the University. During his time at Old Dominion, Brett was involved in the community and committed to groups and events such as the Fellowship of Christian Athletes, the annual All in All the Time Foundation Ruck Walk, and attended River Oak Church. Brett submitted his abstract and plans to participate in the American Society of Biomechanics virtual conference in August 2021.