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The Biomechanics of the Softball Swing in Seven Stages: Optimizing Exit Velocity

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I hereby reaffirm the Lawrence University Honor Code.

Ceara Larson

Abstract

The study of sports biomechanics is a rapidly developing field that can be used to analyze an athlete's most critical motions and improve their performance. In the world of baseball, sports biomechanists, scientists dedicated to the field of sports biomechanics, help keep pitchers healthy, optimize pitch performance, and improve a batter's swing efficiency. Because of their surface-level similarities, the findings of baseball biomechanical studies have been projected onto the sport of women's fastpitch softball, despite their substantial differences in physiology, field dimensions, pitch delivery, and classifications of hitters. The purpose of this study is to produce a biomechanical analysis unique to women's fastpitch softball that helps to guide hitters and coaches in optimizing exit velocity, the speed the ball comes off the bat. Data were collected in two separate experiments in which each batter took 30 at-bats and completed three broad jumps, vertical jumps, and rotational medicine ball throws. The top five exit velocities were recorded and averaged, the furthest distances for broad jump, vertical jump, and rotational medicine ball were kept, and the correlation between these categories were found. Point of impact data was recorded in the second experiment and utilized. Each swing is broken down into seven swing stages and six body sections to complete a more complex analysis. A positive correlation coefficient was reported between both the broad jump and rotational medicine ball throw with exit velocity ($r = 0.49$ and $r = 0.50$ respectively). Point of impact was also evaluated, and an inverse relationship between impact height and exit velocity ($r = -0.57$) was shown. Results indicate the importance of hip and ankle muscle activation in energy production in the swing as well as the need for further study regarding the influence on point of impact in the swing.

Introduction

From the early days of Babe Ruth, sports fans have leapt out of their seats at the sight of a ball soaring through the air and crossing over the fence for a home run. This showmanship of ability was entertaining and led people like Henry Chadwick to create a box score in an effort to identify the best athlete in the game. This scoring system tallies a player's total number of hits, home runs, and bases in a season to generate a concise summary of offensive performance. These data are a foundation for the measurements baseball fans and sports analysts use today, allowing teams to calculate batting average and slugging percentages (SABR, 2021). The measurements recorded indicate the percentage of time a batter reached at least first base from a hit and the average total bases a player records per at bat, respectively. This quickly became the most popular metric for evaluating and ranking hitters (MLB, 2021- A). A specialized field of statistical analysis called sabermetrics, defined as "the search for objective knowledge about baseball", has emerged to further evaluate an athlete's offensive ability as advancements have been made in statistics and baseball alike (SABR 2021). Despite the complex analyses this field can warrant, the statistical measures sabermetrics produce are limited to strictly in-game occurrences and provide little indication of the athlete's tangible athletic ability. To counter this limitation, the field of sports biomechanics was born.

A field with history dating back to the early days of Aristotle, biomechanics has grown into one of the most effective training tools used to improve baseball players in Major League Baseball. Defined as the scientific study of the mechanics of muscular activity, the field continued to develop with da Vinci's investigations of functional anatomy and Marey's study of human activity and the marriage between the body and physics (Clarys, 2003). As the field expanded into the sports world, research studies began to help scientists and the public better understand how a person could perform such amazing athletic feats. Biomechanics research first turned to America's favorite past time in 1961, when the first instances of scientific swing investigation took place during a study conducted with a movie camera and minor league baseball hitters (Welch, 1995). After discovering these opportunities, professional baseball teams have begun to hire sports biomechanists, scientists who specialize in evaluating the high-performance motions of athletes, to evaluate both their own players and the opposing team (Curtis, 2021). The work of these biomechanists has become crucial in player development, prospect evaluation, and injury prevention (Driveline Baseball, 2021). In the face of so much change, the game of softball has been noticeably left behind. Composing only 4% of sports coverage, women's sports are notorious for hosting some of the most elite athletes in the world with the smallest fraction of recognition (Just Women's Sports, 2021). As a result of this disparity, phenomenal hitters such as Lauren Chamberlain, the NCAA career home run record holder (Cadavi, 2020), and Lauren Haeger, the only player to reach 70 career home runs and 70 career pitching wins since Babe Ruth, go unnoticed (Florida Gators, 2015). Through this investigation into the essential movements and muscle groups associated with maximizing exit velocity in female fastpitch softball players, the gap in biomechanical analysis will begin to shrink.

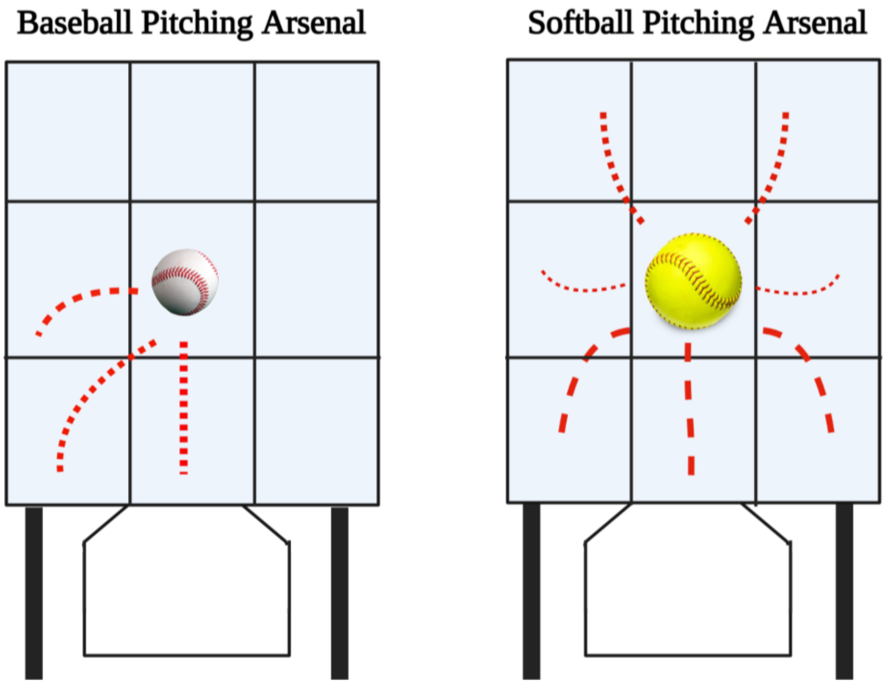
At a fundamental level, baseball and softball are very similar sports. There are nine defensive positions, four bases, and three outs per half inning. During this half inning, the offensive team sends a minimum of three batters to the plate in an attempt to score runs, and the team with the most runs at the end of the game wins. Despite the similarities, the differences that exist between the sports necessitate separate analyses when looking at how to optimize exit velocity in a women's fastpitch softball swing. The primary differences we consider include variances between the dimensions of the sports, novelties in pitching delivery and angles, a specialized classification of softball batters called slappers, and physiological differences between men and women.

Most clear to the casual viewer, baseball and softball have different field and ball dimensions that need to be considered. Perhaps the easiest difference to notice is the ball size between the two sports. With a circumference of 12 inches, a softball is considerably larger than the 9¼ inch circumference of the baseball, and therefore moves much differently when it is hit or pitched. In addition to the variation in ball size, one must also consider the field dimensions. With basepaths of 90 feet (Table 1), a baseball field has fences at a minimum of 325 feet between home plate and the nearest obstruction along the left and right field foul lines, and a minimum of 400 feet between home plate and the nearest fence in center field (MLB, 2021-B). In NCAA Softball, the base paths are 60 feet long and the outfield fences are a minimum of 190 feet from the nearest obstruction at the left and right field foul lines, and 220 feet from the center field fence (Van Kleeck, 2020). With a larger, heavier ball, one would expect to see smaller exit velocity values in softball than in baseball.

Table 1. A summary of the dimensional differences between baseball and softball. Basepath gives the distance from one consecutive base to the other, fence distance (side) reflects the minimum distance between the tip of home plate and the left and right field foul pole and fence, and fence distance (center) shows the distance between the tip of home plate and the midpoint of the outfield fence.

	Ball Circumference	Basepath	Fence Distance (Side)	Fence Distance (Center)	Mound	Mound Distance
Baseball	9 ¼ in	90 ft	Minimum 325 ft	Minimum 400 ft	Raised	60 ft 6 in
Softball	12 in	60 ft	Minimum 190 ft	Minimum 220 ft	Flat	43 ft

As arguably the most important defensive player on the field, the pitcher is tasked with throwing a strike, a ball between the armpits and the knees of the batter that touches a portion of the plate as it crosses to the catcher, to the batter. An effective pitcher is one who creates movement and speed changes that make it more difficult for the batter to hit well. This is accomplished through wrist snaps that cause the ball to break. A breaking pitch is one that rapidly changes direction due to a difference in air resistance on one portion of the ball. Using an overhand delivery on a raised mound, the baseball pitch follows a downward trajectory as it approaches the batter. While it is possible to create an illusion of the ball rising through a backspin that causes the ball to end in a higher position than it would have originally, the average baseball pitcher's arsenal of movement is limited to its downward trajectory and side-to-side movement (Adair, 2002). To some degree, even the side-to-side movement present in baseball is limited to a ball that stays true to its trajectory or a ball that moves away from the pitcher's throwing side. Although not unheard of, the screwball, a ball that breaks in towards the pitcher's throwing side, is among the rarest pitches thrown in baseball due to the strain the grip on the ball puts on the pitcher's arm (MLB, 2021- C). In contrast, due to its release point at the hip rather than overhead, the softball pitch has the capability to break up, down, and to either side of the plate. With the underhand windmill motion, a fastpitch softball pitcher has the opportunity to create air resistance against the ball in more places without causing themselves harm. The most consequential results of this difference are the riseball, a ball that breaks upward due to a rapid backspin produced in the wrist snap of the pitch, and an effective screwball. This leaves the softball batter to make adjustments to their swing in ways the baseball batter does not have to consider.



Baseball Pitching Arsenal

Softball Pitching Arsenal

Figure 1. A visual representation of the possible pitch break for baseball and softball. Figure 1 shows the possible directions a ball from its respective sport can break if it begins in the middle of the strike zone. Pitches can also begin in any of the nine sections and move in the same specified directions. Movement is from a right-handed pitcher. Created with BioRender.com.

These nuances in softball pitching have led to the development of creative "small ball" strategies unique to softball. To overcome her resting inertia, the slapper begins in the left-handed batter's box and begins to run towards the pitcher during her windmill motion. By taking this moving approach to the ball, the slapper is able to take advantage of her speed and slap the ball into the ground. With a closer proximity to first base, the slapper's movement begins at the back of the batter's box and allows them to overcome their resting inertia as they do not stop moving from the first movement of the pitcher until they reach first base. While the average softball player makes it from home to first between 3.5 and 4.0 seconds, slappers make it from home to first in as few as 2.6 seconds (E. Bowman, Personal Communication, February 25, 2021). With the speed of play softball requires, this play puts immense pressure on the defense to make a play quickly. Although they are not typically focused on hitting for power, there are some instances that call for a slapper to hit with maximum exit velocity, making them an important aspect to observe. The investigation we will conduct on slappers will raise a unique consideration for exit velocity optimization when the purpose is to hit the ball on the ground, not over the fence.

Figure 2. A slapper's progression through the box. A left-handed batter follows through the steps to overcome her resting inertia and slap the ball. Photo Illustration created by Bratina.

The final difference we consider is the physiological differences that exist between men and women. In physiological skeletal muscle studies, it is rare for researchers to consider the differences between male and female physiology (Haizlip, 2015). Yet, in an experiment comparing male and female lower limb segment inertial properties, a statistically significant difference was found (Challis, 2012). The difference in inertial properties, or the resistance of the lower half to move from its position at rest, means that any physics-based analyses on the rotational motions of male batters will likely yield different results than in female batters. Additionally, in a study conducted by Haizlip, women were found to have less muscle hypertrophy with comparable strength improvements to the men while participating in the same strength program (2015). With increased hypertrophy comes an increased capacity for ATP production, the primary energy source for cellular respiration. When applied to athletic endeavors, this could indicate that women have a lower capacity for energy storage and therefore must rely on anaerobic respiration more quickly (Proctor, Class Lecture, February 3, 2021). Another notable difference between male and female skeletal muscle was found in the skeletal muscle firing speed and maximum power output. Although male skeletal muscles were typically faster and produced an overall higher maximum power output, female skeletal muscles were found to recover faster and be more fatigue resistant. This resistance to fatigue indicates the possibility of a smaller distribution among the top five exit velocities of a female softball player than the distribution of the top five exit velocities of a male baseball player. With over 3,000 genes expressed differently in skeletal muscle between men and women, the potential for different physical output is high (Haizlip, 2015). It is important to consider the impact these differences could have in sports performance between the two sexes, as we do not yet know the significance of these genes to muscle activation, fatigue, and power. With so many variances in muscle properties, the accuracy in projecting male skeletal muscle outputs and properties onto female athletes needs to be questioned.

Although easily grouped together due to the resemblance in rules and goals, field dimensions, hitting classifications, pitch delivery and movement, and the differences between male and female physiology demand a study unique to softball. Regardless of sport, however, the purpose of the swing is the same: to hit a round ball as far and as hard as possible. Like most complex motions in the body, the swing requires a very specific motor program that sequences a kinetic chain in the body. Motor programming, also known as “muscle memory”, is the brain producing and executing a pattern of neural activity that creates precise movement (Proctor, Class Lecture, February 15, 2021). The work of this paper standardizes the swing into seven swing stages and six characteristic body sections that are essential to producing the optimal exit velocity. In these experiments, exit velocity was correlated with several physical tests for both lower body and abdominal muscle power to examine the importance of lower half and core muscle activation. A positive correlation between these physical tests and exit velocity is anticipated.

The Swing Stages

Every swing has seven characteristic stages that must occur in the process of hitting the ball for it to be considered a full swing. By taking the top five exit velocities per batter, the possibility of a “check” swing or any other abnormalities that would result in less than ideal contact with the ball is limited. Definitions of swing stages were based on field observation, literature review, and informational interviews with reputable swing experts in the baseball and softball world.

In addition to standardizing the sequencing that occurs as an attempt to hit the ball is made, we consider the energy transfer that travels through the body. To maximize exit velocity, a kinetic energy chain beginning in the legs that travels through the pelvis, trunk, and finally arms must occur seamlessly (Sciascia, 2012). Energy is first transferred to the legs through the ground reaction force, which is the force enacted by the ground as the body comes into contact with it. Our hypothesis is that a swing with maximum exit velocity will transfer energy most efficiently to the Swing Acceleration stage (Figure 3) when the barrel of the bat is approaching the ball.

The swing encompasses all motion from the initiation of the swing through the deceleration of the bat after contact. Our seven swing stages are as follows:

A) The Stance
B) The Load
C) Foot Contact
D) Swing Initiation
E) Swing Acceleration
F) Ball Contact
G) Follow Through

The Stance (A) stage is the precursor to all motion and is defined as the subject’s position just prior to the heel coming off the ground. The second stage, the Load (B), begins when the heel of the front leg leaves the ground. Expressed as a step in some subjects and a pivot in others, the movement of the heel initiates a shift in body weight upwards and a slight shift of weight from the front leg onto the back leg. This acts as a timing device for the batter and begins approximately 500 milliseconds prior to contact. This stage is concluded by the front foot heel coming back into contact with the ground, initiating the Foot Contact (C) stage (University of Miami, 2011). At heel contact, the previous weight shift upwards is moved back towards the ground, and a portion of the body's weight is shifted back towards the front side of the body. This stage triggers the rest of the body to begin the next step in the sequence and occurs approximately 340 milliseconds prior to contact (University of Miami, 2011). Next comes the Swing Initiation (D) stage, which is characterized by the first movements of the hands towards the ball, prior to hand rotation. Occurring approximately 127 milliseconds before contact, maximum total ground reaction force is obtained during this stage. The beginning of the Swing Acceleration (E) stage is marked by hand rotation towards the ball, where the wrists accelerate the bat. Here, maximum front foot ground reaction force is obtained. This stage is essential to producing the hand speed that is typically measured prior to contact. The end of this stage is signaled by Ball Contact (F). Ball contact is defined as the duration in which the ball is touching the bat. This stage occurs rapidly and in this study is approximated to the frame just prior to contact and the frame just after contact, a range within 100 milliseconds in either direction. Once the ball leaves contact with the bat, the Follow Through (G) stage begins. In this stage, the body decelerates until it comes to a halt, denoting the end of the swing.

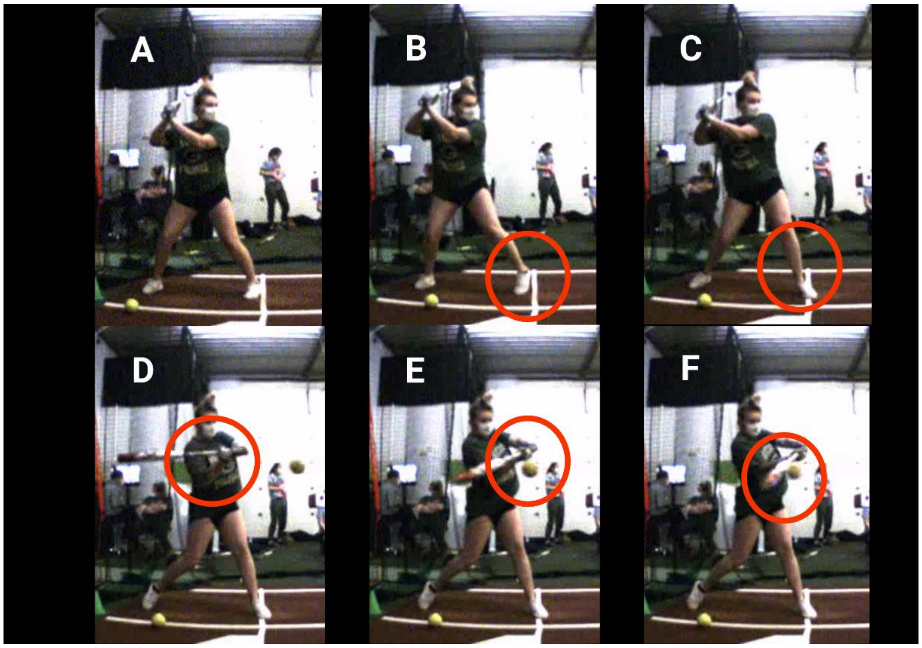


Figure 3. Each swing stage shown with the characteristic movement of each stage, denoted by the red circle. A) Shows the initial stance of the batter. B) Heel leaves the ground. C) Heel comes back into contact with the ground. D) Bottom hand moves the bat towards the ball. E) Top hand rotates the bat towards the ball. F) Ball contact. Created with BioRender.com.

The Body Sections

With established swing stages, we split the body into six sections to facilitate a more thorough analysis and enable easier calculation states. We follow the body sections in the order they transfer energy in the kinetic chain and consider their significance at each stage below. In this study, we analyze the motions of the front leg, back leg, pelvis, torso, front arm, and back arm, respectively. Appendix A gives the formal definitions for each section. Descriptions for the positions of the body will be in terms of an *x*, *y*, and *z* axis, where the origin is at the back point of home plate, the *x-axis* is the line formed from the origin to the front edge of the pitching rubber, the *y-axis* is the line perpendicular to the *x-axis* and is in the plane of the ground, and the *z-axis* is the line perpendicular to the *x-axis* that gives the vertical coordinate of the batter (Figure 4).

The back leg is the first body part to produce ground reaction force utilized in the swing. Beginning perpendicular to the *y-axis* with a slight knee bend ranging from 184 to 206 degrees, the back leg produces the primary ground reaction force during the Load Stage (Stage B), when body weight is shifted to the back side, and continuously through stages D through F, when the batter rotates from the back foot in order to engage the hips into the swing. Although each batter utilizes a different technique to utilize this power, the most critical point for back leg engagement is during Swing Initiation (D) as the force produced travels up the body to the arms. The back leg is also one of the driving forces of the pelvis, transferring its energy along the x-axis to the

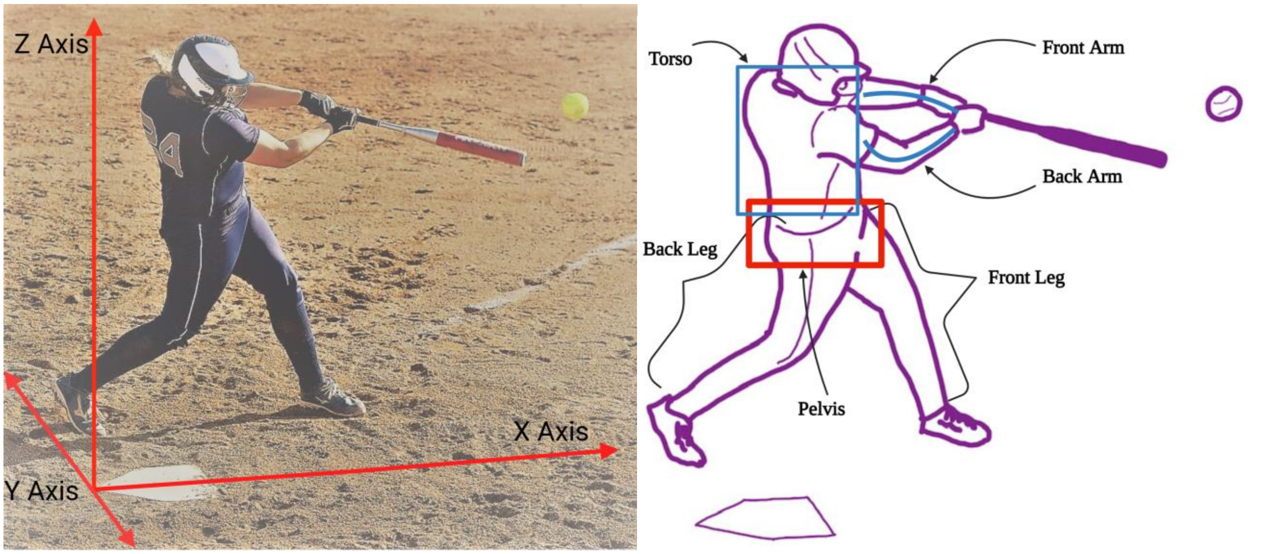


Figure 4: The x, y, and z axes and body sections are shown in relation to a batter at the plate. A) The vertex is located at the back corner of the plate, the *y-axis* is parallel to the front edge of the plate, the *x-axis* is perpendicular to the front edge of the plate, and the *z-axis* is perpendicular to the *x-axis* in the vertical direction. Picture credits to Paul Wilke. Created with BioRender.com. B) A thumbnail sketch shows the six body sections labelled. Sketch credits to Margaret Koker. Created with BioRender.com

rest of the body. During ball contact, it is not uncommon to see a slight shift in this plant as momentum is maximized and the counter force of the moving ball interacts with the body.

The pelvis acts as the link between the upper and lower half of the body during the swing. Beginning with front hip acceleration during the Foot Contact stage (Stage C), the pelvis utilizes the energy transferred from the legs to begin rotation in the *x*-direction. Further energy produced as a torque is created between the upper and lower half of the body during the Swing Initiation stage (Stage D). Tension is relieved as the batter achieves maximum back hip acceleration and front hip deceleration in the Swing Acceleration stage (Stage E). This allows for an energy transfer to the torso that aides in this hand movement.

The torso is the final vessel for this kinetic chain before the energy is transferred into the arms. Measured by the location of the corners of the shoulders, batters will begin the Stance stage (Stage A) with torso perpendicular to the *x-axis* with a slight tilt in the positive *y*-direction towards the plate. From there, the torso does not serve its main purpose until the Swing Initiation stage (Stage D). As the pelvis begins to move towards the pitch, the torso holds its position, causing a rotational torque that produces more energy in the swing. The Swing Acceleration stage (Stage E) is the point where this tension of displacement is released, and the torso transfers this energy into the front and back arm to maximize bat speed to the ball.

The front arm is most essential during the Swing Initiation stage (Stage D), where it dictates the path of the hands through the zone. Beginning between 35 and 55 degrees from the axis of the bat, the front arm does not begin its motion towards the ball until its critical stage when energy is transferred from the torso into the arms. At the beginning of the Swing Acceleration stage (Stage E), the role of the front arm shifts from the primary source of direction to structural support for the back arm. After Ball Contact (Stage F), the front arm will decelerate naturally.

The back arm is the final body section to activate, with its main role serving its purpose during the Swing Acceleration stage (Stage E). Angle ranges on the axis of the bat mimic that of the front arm in initial position, but the back arm does not begin its movement until it is pulled by the front arm during Swing Initiation (Stage D). The first active movements of the back arm characterize the beginning of Swing Acceleration (Stage E) and lead the hands to Ball Contact

(Stage F). The path the back arm produces is essential in creating the ball's launch angle off the bat and is responsible for producing the swing's bat velocity.

Tests for Lower Body Power

Our experiment focuses on the correlations between three physical tests and exit velocity. Tests were chosen for their simplicity, effectiveness, and popularity in the sports community. Each test allows us to examine different measures for lower half power. With limited data regarding the spectrum of muscular power in female athletes and many studies citing the importance of lower half power in the swing, the broad jump, vertical jump, and rotational medicine ball throw allows us to measure the relationship between lower half power exertion and exit velocity (Just Women's Sports, 2021). The primary muscle groups utilized in these tests also allow us to examine their role in producing ground reaction force.

The Rotational Medicine Ball Throw was the first test chosen to correlate with exit velocity due to its mimicry of the most characteristic feature of the swing: the rotation. Utilized in the Speed, Power, Agility, Reaction, and Quickness (SPARQ) rating system, a series of tests that measure physical capabilities of sporting prospects for professional baseball and hockey, this test measures core strength by simulating the rotational core movement utilized to hit the ball (Wood, 2021). In this test, participants are given a 5-pound medicine ball and instructed to stand perpendicular to the throwing axis. With their hands beginning at the belly button, participants hurl the ball forward in an underhand motion as far as they are able, releasing the ball between their hips and armpits. This test was hypothesized to have the strongest correlation to exit velocity since it holds the closest relation to the actual motion of the swing.

The Broad Jump was the second test selected to correlate with exit velocity due to its notoriety and reliability with examining lower half power. This test is a staple in the National Football League Combine due to its unique collection of muscle activation groups in the ankles and hips. Success in this jump is indicative of quadricep, soleus, hamstring, and abdominal muscle strength (Haas, 2019). In this exercise, participants are instructed to leap as far as they can horizontally and land with both feet on the ground in a balanced position. This motion mimics the explosive power required of the pelvis and legs during the swing as well as the stabilization required during the quick torque of the pelvis and torso to stay upright during the Swing Initiation (D) and Acceleration (E) stages. Estimating that this test would not relate closely to the rotation of the swing, a hypothesis was formed that the broad jump would hold a moderate correlation with exit velocity but a lower correlation than that of the rotational medicine ball throw correlation.

The Vertical Jump was the final test chosen to evaluate power in the lower half of the body. The purpose of this test was to examine the importance of the unique muscle attributes that enable optimal exit velocity. With performance determined by muscle strength characteristics surrounding the lower limb joints, the Vertical Jump relies on maximizing joint moments, power, and work done in the ankle, knee, and hip (PTDirect, 2021). This test imitates the energy transfer and the usage of fast twitch muscles in the lower half of the body, illustrating the importance of an effective kinetic chain. A secondary test for a diverse group of leg and hip muscles allows for a more holistic analysis. In this test, athletes begin approximately four feet in front of the measuring instrument and take two steps: one to create momentum and another to plant the feet together and swing the arms prior to jumping. The objective of the Vertical Jump is to leap off the ground as high as they are able along the z-axis. Much like the broad jump, a hypothesis that a moderate correlation with exit velocity in the swing due to the overlap in muscle groups used between the two motions and the relation it holds to the agility fast twitch muscles provide in the swing was adapted.

The work of this paper utilizes data from two experiments to analyze the swing through stages and body sections, correlate kinetic chain transfer with exit velocity, and evaluate the importance of lower body power throughout. The stage-by-stage analysis will evaluate which steps of the swing dictate the kinetic energy chain and ask what significance the arms and elbows have in exit velocity production. By conducting a study dedicated to softball, factors projected onto softball players by previous baseball studies will be challenged. Finally, the three tests for power will evaluate the significance of lower body and core power in producing maximum exit velocity.

Methods

Experiment 1:

Participants

Physically healthy women between the ages of 14 and 23 years of age were recruited to participate in this study. Stipulations for participation included good physical condition such that they could optimally perform each test, a minimum of three years of competitive softball experience, and the ability to optimally hit a pitch released from a pitching machine at a speed of 55 miles per hour. This ability was screened for based upon age and softball experience and reassessed during data collection of each participant. A total of 41 subjects participated in Experiment 1. Consent was given for full usage of any data, video, or photos collected for the duration of data collection.

Set-Up and Materials

All participants were instructed to warm up on their own accord such that they were adequately prepared to physically exert themselves to the best of their ability while swinging, jumping, and throwing. Fifty yards of turf, netting, a softball tee, and softballs were provided to them and an unlimited amount of time. Participants provided their own bat, helmet, and gloves as needed. A measuring tape stretching 40 feet was extended and secured to the turf to allow for broad jump and rotational medicine ball throw data collection. The rotational medicine ball throw was conducted using a five-pound medicine ball. An additional measuring tape was stretched to 15 feet and secured to the edge of an adjacent wall such that participants could jump maximally and touch the tape measure with their right hand before falling into the open space to the left of the corner of the wall. In a nearby pitching lane, the HitTrax swing analysis system was calibrated (HitTrax, 2021-B). The system was calibrated to a home plate sitting 37 feet away from our pitching machine and its connected monitor was angled so that the batter could not see their results during their hitting session. The pitching machine was set at 55 miles per hour and was adjusted to mimic a pitch waist high and down the middle of the plate. Pitch speed was kept constant, however pitch location could be altered at the batter's request. 12 inch Juggs © pitching machine dimpled balls were fed into the machine.

Procedure

In groups of up to three athletes, participants completed our separate tests sequentially in the order of broad jump, rotational medicine ball throw, vertical jump, and finally swinging. Groups were formed based on participant availability and scheduling capacity, and the order in which these athletes performed the test was kept consistent throughout their testing time.

Athletes were given three trials of broad jump, where they were instructed to jump as far as they were able horizontally. Participants were allowed to use their arms to produce momentum so long as their feet were stationary until leaving the ground for the jump. Upon landing, only jumps in which both feet stuck to the ground were accepted, and the point of the heel closest to the starting point was recorded as the jump length. If the landing was not stuck, a re-try was given until the participant could provide three quality jumps. The furthest distance of the three trials was recorded and used for data analysis.

Explicit instructions and a demonstration were shown to each participant prior to their rotational medicine ball testing. Participants began with their feet parallel with the tape measure and their front foot behind point zero. Orienting their feet to mimic their stance in a batter’s box, athletes were required to release the medicine ball between their hips and armpits while keeping their posterior hand in the “underhand” position. If these conditions were not met, a re-try was given until three viable throws were completed by the participant. Landing spot of each throw was spotted by two researchers and the average point between both points was recorded. The best of three throws was recorded and used for data analysis.

Prior to vertical jump, participants had their reach measured. With a relaxed shoulder, subjects raised their right hand above their head and the initial position was recorded. Athletes were then instructed to take a two-step approach and leap as far as they could vertically before touching the tape measurer. The difference between this initial reach and their jump touch was taken and recorded as their vertical jump height. The best of three jumps was recorded and used for data analysis.

To complete testing, participants completed 30 at-bats as logged by the HitTrax system. Speed was kept constant among all athletes and height was adjusted according to athlete preference. Subjects were given as much time as was needed to complete all 30 at bats, and the top five exit velocity swings were recorded. With each swing, exit velocity, point of impact, and launch angle were collected and utilized in data analysis.

Data Analysis

Data sheets produced by HitTrax were combined with our testing data sheets to create one data set that was uploaded into R Studio for statistical analysis. A summary of results can be found in Table 2 and Figure 4 in the Results section. Pearson, Kendall, and Spearman tests for correlation were conducted after checking for normality (Whitlock, 2014). A scatter plot showing these correlational values was produced for broad jump, vertical jump, and rotational medicine ball throw with exit velocity in Figure 5. Correlational coefficients were recorded and reported in Table 2.

Experiment 2:

Participants

Nine members of the Lawrence University Fastpitch Softball Team were recruited to participate in a secondary study. Ages ranged from 18 to 22 years old, and the minimum competitive softball experience was three years. All participants were healthy and fully able to perform the physical tests requested of them.

Set Up and Materials

The set-up for the broad jump, rotational medicine ball throw, and vertical jump were kept consistent with Experiment 1. A HitTrax system calibrated to a home plate 20 feet in front of a protection screen was placed in the available pitching lane. Configured to align with each at bat, a high-speed camera was placed perpendicular to the batter. A line was established at the front of home plate, and athletes were instructed to swing such that their front foot aligned with the front of the plate for the duration of their swing. A single volunteer threw front toss to all participants using 12 inch Rawlings softballs with similar variability to the pitching machine.

Procedure

Procedure for Experiment 2 was followed in the exact order as conducted with Experiment 1. The nine participants were divided into groups of three for the duration of testing. The top five exit velocity swings were taken for data collection, and the exit velocity, launch angle, and point of impact was taken to complete data analysis.

Data Analysis

Degree angles were taken from video data collected during Experiment 2. Angles were taken at each swing stage of each batter's top five exit velocities. Hip and shoulder points were taken by points of reference on the hitter's body. The hip point was defined as the visible point in which the leg angle differs from the torso angle. The shoulder point was defined as the visible point in which the torso angle differs from the arm angle. These values were utilized for initial position values found in the body section of the introduction.

Statistical tests were conducted using RStudio moments package. Tests used included a Shapiro test for normality and Wilcox test to determine a difference in medians. Four exit velocity tiers were created for further data analysis labelled 1 through 4. Exit velocity groupings are as follows: Tier 1- 50.4 through 57.9 miles per hour, Tier 2- 58.4 through 63.3 miles per hour, Tier 3- 63.5 through 65.4 miles per hour, and Tier 4- 65.5 through 69.3 miles per hour. Box plots were created for each point of impact axis versus exit velocity tiers. A three-dimensional plot was created following these same tiers, and a second three-dimensional plot was created ranking an individual hitter's top five exit velocities from 1 to 5.

Results

Experiment 1:

Of the 41 participants from Experiment 1, 23 had a minimum of 10 years of travel softball experience, with the overall average (± 1 standard deviation) years played at 10.0 ± 2.7 years among participants. Such high level of experience provided the experiment with well-practiced and consistent swings. Despite the age range from 14-22 years old, athletes averaged an exit velocity of 63.1 ± 4.8 miles per hour. Consistent with the hypothesis that recorded exit velocities would show an even distribution, a Shapiro Test for Normality gave a 0.35 p-value, indicating that the data were normally distributed. The same was true for both the vertical jump and rotational medicine ball throw, which provided p-values of 0.61 and 0.053 respectively (Table 2).

Table 2. A summary of the results from Experiment 1. All calculations were conducted using RStudio. Average represents the mean value among the data set and standard deviation represents the average distance from the mean. Normality p-values were calculated using the Shapiro Test for normality. Correlation coefficients and p-values were calculated using the Pearson, Kendall, and Spearman tests for correlation.

	Average	Standard Deviation	Normality P-Value	Correlation Coefficient	Coefficient P-Value
Exit Velocity (mph)	63.1	± 4.8	0.349		
Broad Jump (m)	1.76	± 0.21	0.0391	0.49	0.0011
Vertical Jump (m)	0.411	± 0.071	0.614	0.19	0.2301
Rotational Medicine Ball Throw (m)	6.02	± 1.3	0.0533	0.50	0.0008

Using the Spearman’s Test for Correlation, a 0.49 correlational coefficient was calculated between the broad jump and exit velocity, indicating a moderate correlation. The same conclusion can be made for the rotational medicine ball throw, which yielded a statistically significant 0.50 correlational coefficient when tested against exit velocity in Pearson’s Test for Correlation. Despite its normal distribution, the vertical jump was the only statistically insignificant result with a 0.19 correlational coefficient found that yielded a p-value of 0.23 from Pearson’s Test for Correlation (Table 2).

The scatterplot produced between exit velocity and the physical tests conducted during Experiment 1 show a distinct positive slope of 0.50 and 0.49 in both the rotational medicine ball throw and broad jump plots, respectively (Figure 5). The standard deviation, indicated by the shaded region of the plot, gives a marginally smaller relative distribution in the rotational medicine ball throw plot than the broad jump plot. The blue plots indicate a statistically significant correlation while the red plot indicates a plot that is not statistically significant.

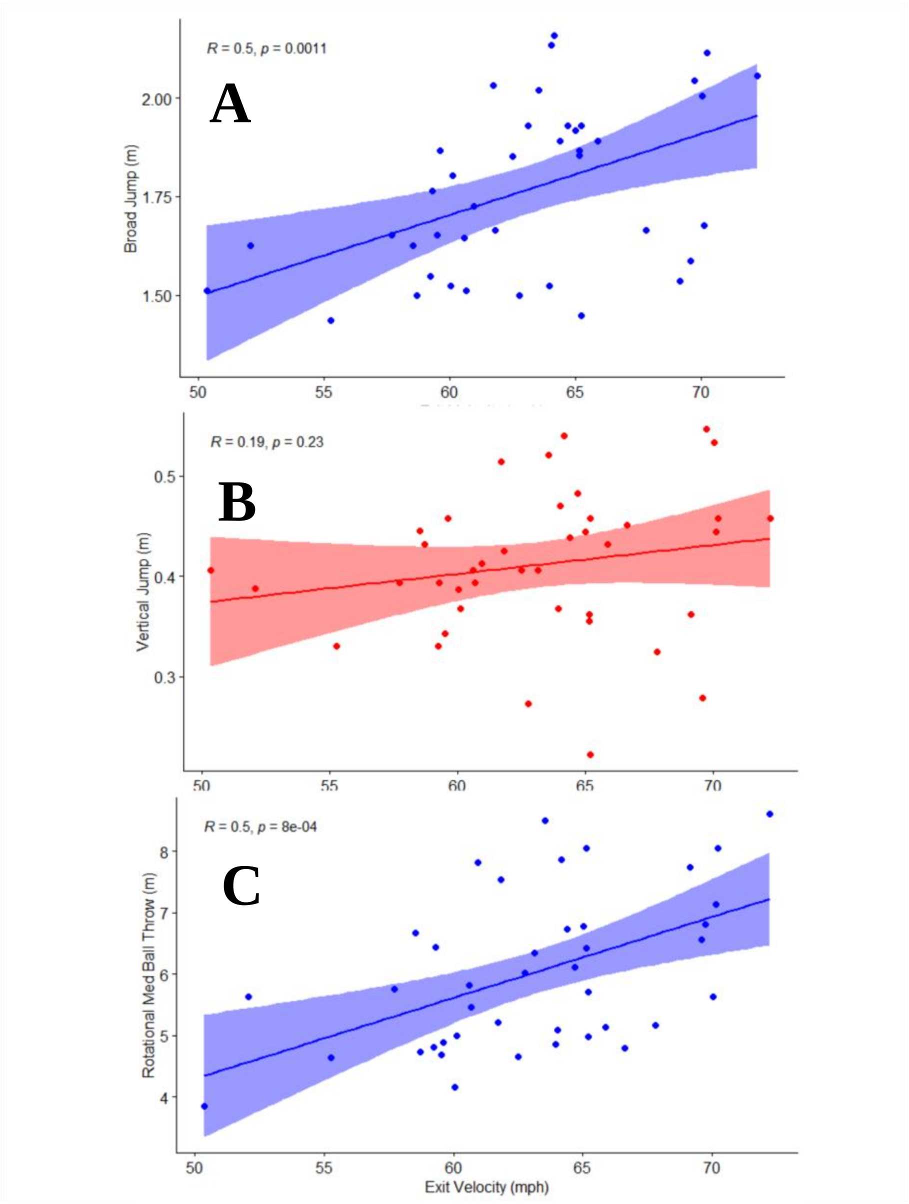


Figure 5. Correlational Coefficient Scatterplot. A scatter plot between each of our physical tests and exit velocity was plotted. Slopes in blue denote statistically significant correlational coefficients and the slope in red represents a slope without statistically significant correlational coefficients. A) The correlation between broad jump and exit velocity, r = 0.49. B) The correlation between vertical jump and exit velocity, r = 0.19. Results are not statistically significant. C) The correlation between rotational medicine ball throw and exit velocity, r = 0.50. Figure created using Biorender.com

Experiment 2:

With eight participants in Experiment 2, a median exit velocity of 63.4 miles per hour was found. Six of the eight participants had over eight years of experience, with the minimum experience at five years in the athlete pool with ages ranging from 18-22 years of age. A Shapiro Test for Normality revealed only one variable that was normally distributed, Point of Impact on the *y-axis* (POI Y), with a p-value of 0.49. Exit Velocity (EV), Point of Impact on the *x-axis* (POI X), and Point of Impact on the *z-axis* (POI Z) were not normally distributed with p-values falling below 0.05. For analysis, exit velocities were split into four tiers from lowest to highest exit velocities. Tier 1 had exit velocities ranging from 50.4 to 57.9 miles per hour, Tier 2 had exit velocities ranging from 58.4 to 63.3 miles per hour, Tier 3 ranged from 63.5 to 65.4 miles per hour, and Tier 4 from 65.5 to 69.3 miles per hour. The spread of the medians was looked at to examine the most commonly hit pitch.

A linear model constructed with exit velocity as the dependent variable and the *x*, *y*, and *z* points of impact as the independent variables revealed a statistically significant relationship between exit velocity and contact height (POI Z). For every one inch increase in distance from the top of the strike zone, the exit velocity decreases by 0.57 miles per hour on average while holding all other variables constant, as indicated by the negative coefficient produced in the model. A similar negative relationship was found among the *x*- and *y*- points of impact with coefficients of -0.13 and -0.39 respectively, however without statistically significant results more testing is required.

POI X had the smallest distribution of medians between tiers with medians ranging from zero to two inches in front of home plate (Figure 6). Among these tiers, *x-axis* point of impact had the furthest spread in Tier 3 and Tier 4 with 50% of the balls struck between 63.5 and 65.4 miles per hour impacted between two and 14.5 inches in front of home plate, and 50% of the balls struck between 65.5 and 69.3 miles per hour contacted between one inch in front of home plate to six inches behind the front of home plate. Two outliers were discovered in POI X, with an extreme outlier in Tier 4 had a depth of impact nearly 30 inches behind the front of home plate and an outlier in Tier 2 which was struck 11 inches in front of home plate.

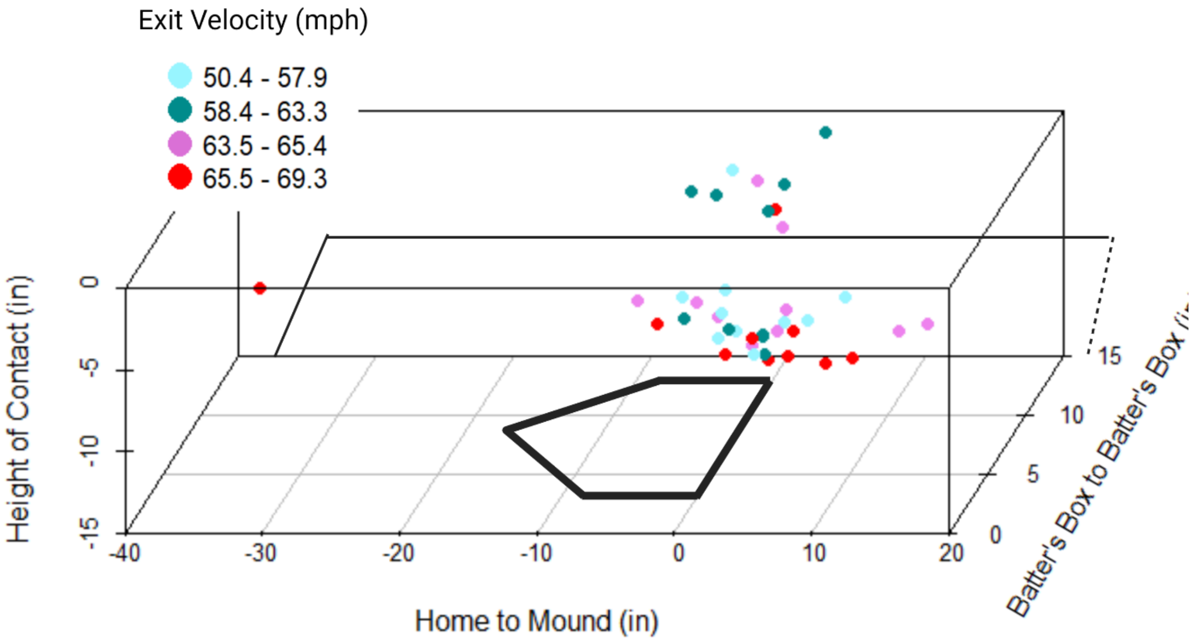


Figure 6. A three-dimensional point of impact plot. Exit velocities were split up into four tiers and plotted using the POI X, POI Y, and POI Z coordinates taken during data collection. Created with BioRender.com.

Point of impact on the *y-axis* (POI Y) yielded a smaller range of values due to the limitations of reach and dimensions from batter's box to batter's box. Despite this difference between POI Y and POI X, the median points of impact between the four tiers had a slightly wider distribution than POI X with median values ranging from 7.0 to 9.5 inches on the POI Y axis. In contrast to POI X results, the furthest spread of values was in the two central tiers, Tier 2 and Tier 3. In Tier 2, 50% of the balls impacted were hit between 2.0 and 7.0 inches on the POI Y axis, and Tier 3 held 50% of its values between 2.0 and 7.5 inches. Only one outlier in Tier 4 was found at 0.0 inches.

The widest distribution of medians was in the POI Z data points. Medians ranged from 2.5 to 11 inches below the top of the strike zone. A wide spread of points existed in tiers 1, 2, and 3, but the spread of points in Tier 4 was limited to strictly the lower half of the strike zone. 25% of the balls struck between 65.5 and 69.3 miles per hour were struck between 13 and 15 inches below the top of the strike zone, while 75% of them were 8.5 inches below the top of the strike zone or lower. Despite this concentrated spread, one outlier exists at zero inches from the top of the zone in Tier 4.

Point of Impact data also showed a wide distribution of hard-hit balls that were struck in different positions. Of the 20 swings collected with exit velocities over 63.5 miles per hour, 16 of them were struck between seven and 15 inches below the top of the strike zone, in the lower half of the zone. In contrast, of the 9 swings collected with an exit velocity below 58.0 miles per hour, five of them had contact between zero and five inches below the top of the strike zone. Upon ranking a specific batter's top five exit velocities and plotting their point of impact, this trend changed. With the exception of one outlier, a batter's hardest contact came a minimum of five inches behind the front of the plate. The swings with the greatest exit velocities as a group in Figure 7 showed only the second or third highest exit velocity from an individual batter. The lowest of the top five exit velocities a batter produced showed a much more sporadic distribution with each individual lowest exit velocity falling in a different quadrant. Of the values for the second and third highest exit velocities per batter, however, 14 of the 18 swings fell between -5 and -10 inches on the *z-axis* as compared to two of the seven highest exit velocities on the same range of the *z-axis*.

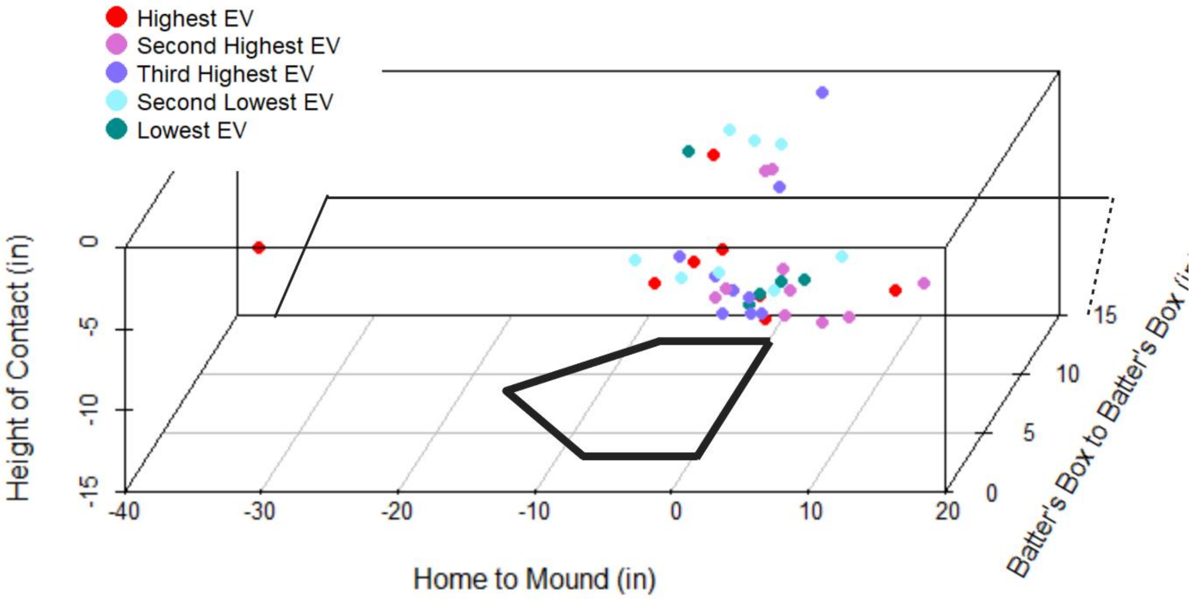


Figure 7. A three-dimensional point of impact plot ranking an individual's top five exit velocities. Each participant's top five exit velocities were ranked from 1 to 5 and plotted according to ranking achieved. Coordinates for POI X, POI Y, and POI Z were used to create the three-dimensional plot. Created with BioRender.com

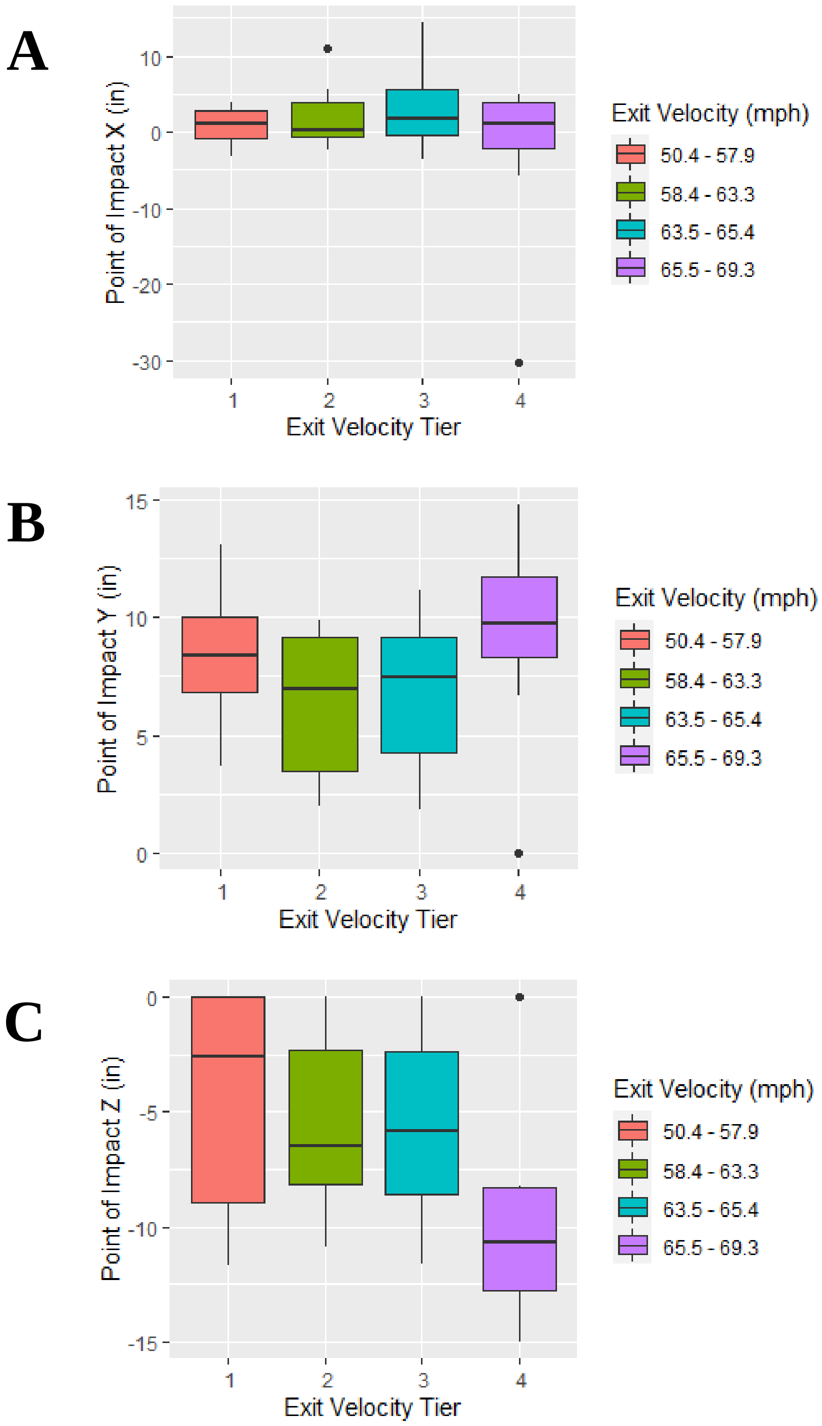


Figure 8. A comparison of distributions between POI and Exit Velocity. A boxplot was created to show the median values, denoted by the line through the box, 50% of the distribution of points, shown as the colored boxes, and the outer 25% of distribution, depicted as the whiskers. Outliers are shown by a single black dot. Created with BioRender.com. A) Point of Impact on the *x-axis* and exit velocity. B) Point of impact on the *y-axis* and exit velocity. C) Point of impact on the *z-axis* and exit velocity.

Discussion

The kinetic energy chain, sometimes referred to as the kinetic link, is the transfer of energy and momentum from one body segment to the next. The use of muscular force in the swing accelerates the ascending muscles by using the energy from the deceleration of the previous muscle (Welch, 1995). To maximize exit velocity, a hitter must optimize this energy transfer into the hands as the bat accelerates to the ball at contact. Positive correlational coefficients found between exit velocity, broad jump and rotational medicine ball throw in Experiment 1 indicate this kinetic chain transfer, while the relationship between pitch height and exit velocity found in Experiment 2 show the importance of timing with this transfer.

Experiment 1:

The relationship between broad jump, vertical jump, and rotational medicine ball throw with exit velocity was investigated and a positive correlation was found for two of the three statistical tests. Broad jump and rotational medicine ball throw had higher correlation coefficients of 0.49 and 0.50 respectively, while vertical jump had a correlation coefficient of 0.19 that was not statistically significant. Literature on the muscle contraction order in jumps discuss an order of muscle contraction different from everyday actions, such as walking or sitting. In normal sequential actions of the body, muscles contract proximally to distally in the body, thus the presence of specialized muscle contraction in both our physical tests and exit velocity create a closer relationship between these motions (Robertson, 1987). Each test aligns most closely with a particular set of swing stages and muscle groups, as outlined below.

Broad Jump:

The broad jump was tested among athletes as a means of measuring lower half power. Primary literature indicates that hip and ankle joints are of high importance during broad jump performance. In a standing broad jump, it was found that just over 45% of the work produced from lower half joint muscles came from the hip joints, and 50.2% of the work originated from the ankle joints (Robertson, 1987). These results identified the hip and ankle joints as primary work producers, while the very low work producing knee joint (3.9% work contributed) as an energy absorber. In the softball swing, a moderate correlation coefficient (r = 0.49) indicates that hip and ankle joints could also be responsible for producing a large portion of the work from the lower half of the body.

In an effective kinetic energy chain executed in the swing, this work would be produced during the Load stage (B) and the Foot Contact stage (C) when the upper body is stationary. This evidence is further supported when considering that during the Load stage (B), the front leg heel is off the ground, leaving the back leg to stabilize the body. As motions following the same body sequence in the lower half, studies on baseball pitching are utilized to make conclusions about the swing. In a study conducted on elite baseball pitchers and the ground reaction force (GRF) produced, it was discovered that ground reaction force is maximized in their back leg just prior to contact (Robb, 2010). Despite the smaller foot stride in the swing, the lateral hip movement between these two motions is largely the same, and therefore will produce a very similar GRF. In the study mentioned above, the pitchers who produces the largest ground reaction force correlated with the pitchers who had the highest pitch velocity. A separate study on baseball pitchers examining the arc of rotation of the hips links the kinetic energy sequence of the body between the hands and the hips and finds a 0.50 correlation coefficient between non-dominant hip rotation with ball velocity (MacWilliams, 1998). Combining this link found between hip rotation and hand speed with the results of the GRF with pitch velocity, one could hypothesize that these same hip and ankle factors that are so prominent in lower half power production in pitching contribute to a higher exit velocity in the swing. Also discussed in the 2010 study is evidence that muscle activation fires from the ground up, supporting the existence of a kinetic energy chain flowing throughout the body (Robb, 2010). One possible avenue for further study is a correlational study between overhand throwing velocity and swinging exit velocity in softball players to support this hypothesis.

Rotational Medicine Ball Throw:

Addressing the turning aspect of the swing, the rotational medicine ball throw yielded a 0.50 correlation coefficient against exit velocity. In the pelvis, non-dominant hip rotation that begins in the Swing Initiation Stage (D), produces a torque between the pelvis and the torso

(MacWilliams, 1998). Not only does this resistance create potential energy that will eventually travel to the hands of the swing, but the rotation of the hips produces kinetic energy that will continue the kinetic energy chain in the swing sequence. In the torso, recent literature suggests that the core muscles in the abdomen drive the kinetic chain function and transfer in the body (Sciascia, 2012). The moderate correlation coefficient produced in this study supports this notion. In a study that compared long distance throwers versus short distance throwers with this particular method, results indicated a longer and larger pectoralis major muscle activation, particularly in the rotational side of the thrower. Additionally, successful rotational medicine ball throwers, those who threw in the upper quarter of distances showed over twice the amount of muscle activation in the left external oblique than participants who threw the shortest distances across the study (Ikeda, 2009).

During the Swing Initiation Stage (D), the torso must be stabilized as the pelvis begins its movement prior to the torso beginning its movement. A study conducted examining the effect core muscle strengthening has on healing back injuries indicates that the muscles of the core and abdomen are in part responsible for this stabilization as the torque increases (Petrofsky, 2008). In the Swing Acceleration Stage (E), the tension between the pelvis and the torso is released as the torso uncoils itself to go back to its resting state. The quicker this recoil occurs, the faster the hands move to the ball and therefore a higher exit velocity will be produced. Speed of elastic recoil in muscles is dictated by muscle strength, thus increased strength in the rotational muscles of the pectoralis major and external oblique would produce increased exit velocity, as predicted by further rotational medicine ball throw distance (Ikeda, 2009). If there were any inefficiencies in the energy transfer from this recoil into the arms of the swing, however, this would result in an imperfect correlation like the results this experiment showed.

Vertical Jump:

Although still a positive correlation, the relationship between the vertical jump and exit velocity was much weaker with a correlation coefficient at r = 0.19, which was not statistically significant. In the same study that observed the percentage of work produced by lower body joints in the standing broad jump, work produced percentages were found for the standing vertical jump. Contrasting the broad jump counterpart, 24.2% of the work produced in the vertical jump was contributed by the knee joint, and only 35.8 % of the work produced came from the ankle joint (Robertson, 1987). An electromyography study observing the specific muscle activation in vertical jumping identified one of the major muscles involved is the biceps femoris, which is responsible for knee flexion (Pereira, 2008). This muscle performs to a much weaker degree during hip extension, which the hip performs for the duration of swing stages B through D (TopVelocity.net, 2018). While the positive correlation that exists can be attributed to the overlap between energy produced in the hips and ankles between the broad jump and vertical jump, the lower correlation coefficient could be attributed to the reduced strength capacity of the biceps femoris or the lack of importance the biceps femoris has in energy production in the lower half of the body. If the biceps femoris were handicapped by hip extension during the swing, this would negatively affect energy production in the front leg, back leg, and pelvis, taking energy away from the swing and lowering exit velocity. Since no negative correlation was found, this possibility can be ruled out and the reduced correlation can be attributed to specific muscle relevance in the swing.

Experiment 2:

The purpose of Experiment 2 was to conduct a study and make conclusions regarding the optimal point of impact to maximize exit velocity. An analysis of the difference in medians revealed only a 2.0 and a 2.5 inch distribution in POI X and POI Y respectively, and a much larger 8.5 inch distribution in POI Z. A linear regression dependent on exit velocity showed a negative relationship between all three points of impact, although the only statistically significant result was in the POI Z. These results were further supported with a three-dimensional plot analysis, which revealed a large portion of the group's hardest hit balls to be struck in the lower half of the zone (Figure 6). When adjusted to consider an individual hitter's hardest hit balls ranked from one to five, the three-dimensional plot revealed that the group's contact point of the softest hit exit velocities considered were highly variable (Figure 7).

In limited observational studies on point of impact, typically only POI X is considered as contact along the *x-axis* is associated with timing and is therefore one of the most easily made adjustments among hitters. Despite the common teaching of young hitters to hit the ball in front of the front foot, between 0.0 and 2.0 inches in this study, Experiment 2 results indicate no statistically significant relationship between depth of contact and exit velocity (B. Banker, Personal Communication, December 12, 2020). One possible explanation for this lack of relationship is that depth of contact is determined by timing of the swing, not necessarily the biomechanics of the swing. This possibility is further supported in a case study conducted by HitTrax on a high school baseball player. With only an adjustment to athlete's timing of his swing, the hitter yielded a 2.7 miles per hour average increase in exit velocity. POI X data indicated contact in front of home plate 92% of the time in the second hitting session as compared to the 9% proportion of contact in front of home plate during the first session (HitTrax, 2021, A). More research is needed to determine the cause of this difference, but one possible cause is a cited difference between male and female thorax and pelvis motion, which would affect the total kinetic energy at the point of impact (Landlinger, 2010).

The small distribution of medians among exit velocity tiers between 7.0 and 9.5 inches on the *y-axis* lies in the region of the plate considered down the middle or on the inside half of the plate to the right-handed batter. As the batters were instructed to only swing at pitches in which they thought they could hit with maximum exit velocity, these results indicate an athlete preference for this pitch placement. These results are consistent with POI X findings, as hitters are taught to make contact with an inside pitch earlier than an outside pitch (B. Banker, Personal Communication, December 12, 2020). Like the results of POI X, perhaps the reasoning for this statistically insignificant relationship is the emphasis on timing with very little change in hand path for a pitch that is inside or outside to the batter.

The largest difference in exit velocity tiers point of impact was found in the *z-axis* contact points. In Tier 4, the highest exit velocity tiers, all values were located in the lower half of values along the *z-axis*. With a median distribution of 8.5 inches between Tier 1 and Tier 4, exit velocities between 50.4 and 65.4 miles per hour showed no difference in spread, meaning that only the best exit velocities of the data set had a preference for low pitches. Figure 6 was created to address the possibility of one or two individual, stronger participant preference, and results still showed a high proportion of athlete's individual top 3 exit velocities in the lower half of the zone. Additionally, the only statistically significant relationship discovered in the linear model was between exit velocity and POI Z. A negative coefficient for this relationship shows an inverse relationship, with every 0.57 inch decrease in *z-axis* point of impact creating a one mile per hour increase in exit velocity on average while all other variables are held constant. Limited sources on pitch contact height necessitates further study to investigate this relationship, however one possible explanation for this relationship is in the adjustment the body has to make to create an impact at different pitch heights. A swing at a low pitch can be approximated to mimic the motion of the golf swing. Typically referred to as the "X-Factor" in the golf swing rather than the kinetic energy chain, research shows increased pelvic restriction and trunk rotation in elite golfers (Cole, 2016). Perhaps with a lower pitch that mimics the contact point of a golf swing, a batter has additional time to maximize the torque between the pelvis and torso, allowing for greater energy production and transfer.

Questions for Further Study and Possible Sources of Error:

Like all complex motions in sports, the softball swing is an intricate sequence that can be affected by an infinite number of factors. A batter's exit velocity varies day by day and depends on factors such as muscle tightness, mental capacity to choose proper pitches, their ability to track the ball, and even the type of ball contact is being made with. Having done two experiments that utilized different styles of ball (dimpled machine balls versus hard softballs), one direction for future study is quantitatively analyzing the difference in contact between the two swings. This information could help coaches and athletes make informed decisions regarding the best training methods to prepare for game time. Another possible direction for further study would be a comparison study that examined a batter's top five exit velocity swings to their bottom five exit velocity swings. This comparison could address potential discrepancies between hand path, energy transfer, timing, or pitch selection that this study had to factor out.

The analysis of the slapper was left largely unanswered in this study. With only three slappers in the data set, it was very difficult to standardize and make real conclusions regarding their swing patterns. A slapper's goal in a game is typically to put the ball in play in a precise location rather than with optimal contact, meaning it is unusual to find an at bat in which a slapper is swinging with maximum hand speed. A swing study dedicated solely to slappers that categorized the different caliber of contacts that they are capable of would address some of the same questions this study observed. Primarily, questions for further study would include how a slapper's swing sequence is affected once their feet begin moving through the box, if maximum exit velocity swings with low launch angle values would produce a desired outcome, and if there is a pitch location ideal for a slapper to make contact while optimizing exit velocity. Additionally, a comparison study between a power slap, a slap in which the batter is only attempting to get on base, and a regular power hitter would provide interesting insight to the advantages or disadvantages moving one's feet in the box has on exit velocity.

One factor the experiments were unable to account for is the effect of competitiveness in the athletes who participated in this study. In the first experiment, results could have been different among athletes who performed in a group that they could compete with or when they performed alone. Despite best efforts, there were several groups of participants who completed their testing without a full group of three. Without some of their peers around them, it is possible that they did not push themselves to the same level of competitiveness that would be shown in a game, therefore producing lower results than what they are capable of. Additionally, the presence of athletes from varying age groups could have affected results as an athlete may change her performance based on social expectations. Fear of being judged by peers, expectations of skill level based on age, or the need to "show off" for older or younger athletes could have resulted in altered performance. In future studies, standardizing that each participant performs the tests alone could eliminate this possibility.

The standardized speed of the pitching machine and underhand toss of the front-tosser is another factor to be considered in producing optimal performance from each athlete. To ensure that a batter did not have extra beginning momentum from the ball in a faster pitch, a standard speed of 55 miles per hour was set. While this speed was picked as a middle ground between average high school and average college speed of the participants, difficulty of timing varied per batter. A future study might consider creating tiered age groupings that each have a standard speed evaluated by age group.

Another possible source of error was in the rotational medicine ball throw itself. In general, people had trouble performing and understanding how to perform it. Even though a demonstration was given and the same explanation was given to each participant, there were many throws that were line drives or balls that were thrown straight into the ground rather than for distance. This could be accounted for by taking the exit velocity of the medicine ball as it leaves the participants hand rather than distance in a future study, however this would also not be a perfect approximation with the tools that were available to us.

The findings of this study encourage further studies evaluating the improvements different training methods could make in exit velocity. In the future, a longitudinal study that observes swings before and after a hip strengthening program or an ankle strengthening program in female athletes would add value to the body of literature that currently exists.

A final avenue of future study lies in the usage of different data collection tools. An electromyographical study that took electrical impulse readings of muscle activations and correlated lower half muscle activation with exit velocity would provide further contextual support to our study. Placing participants on a force plate such that the ground reaction forces could be evaluated at each swing stage would also provide more information on the essential factors necessary to producing optimal exit velocity. An eye track system on the batter would provide further insight into the head and shoulder movement en route to making contact with the ball.

Conclusions:

The work of this study was to evaluate the essential factors to maximizing exit velocity in female fastpitch softball batters. A positive correlation found between exit velocity and broad jump prove the importance of hip and ankle joint muscle activation to energy production in the swing, and the positive rotational medicine ball throw correlation demonstrates the need for torque between the pelvis and the torso to facilitate further energy transfer. Point of impact data was also investigated, and an inverse relationship between ball contact height and exit velocity was discovered. These findings indicate a change in swing form to adjust for pitch height, but not for pitch depth or width.

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Appendix A

Body Section	**Definition**
Front Leg	The bottom limb closest to the pitcher. Ranges from the hip joint through the metatarsals. Major muscle groups include: quadriceps, hamstrings, gastrocnemius, soleus
Back Leg	The bottom limb furthest from the pitcher. Ranges from the hip joint through the metatarsals. Major muscle groups include: quadriceps, hamstrings, gastrocnemius, soleus
Pelvis	The joining point for the front and back legs with the torso of the body. Consists of the Pelvic Girdle. Major muscle groups include: gluteus medius, gluteus maximus, sartoius
Torso	The link from the pelvis to the base of the neck. Includes the vertebrate, rib cage, clavicle, and scapula. Major muscle groups include: latissimus dorsi, serratus anterior, internal abdominal oblique, external abdominal oblique, rectus abdominis, trapezius, deltoid, rhomboid
Front Arm	The top limb closest to the pitcher. Ranges from the humerus through the metacarpals. Major muscle groups include: triceps brachii, biceps brachii, brachio-radialis, flexor carpi radialis, extensor carpi ulnaris
Back Arm	The top limb furthest from the pitcher. Ranges from the humerus through the metacarpals. Major muscle groups include: triceps brachii, biceps brachii, brachio-radialis, flexor carpi radialis, extensor carpi ulnaris

Appendix B: Coding

Correlation Coding:

~~~
```{r setup, include=FALSE}
knitr::opts_chunk$set(echo = FALSE, message=FALSE, warning=FALSE)
```


```{r}
# load pacakages and read in your data.
library(tidyverse)
library(readr)
library(GGally)
library(corrplot)
#install.packages("ggpubr")
#install.packages(corrplot)
library("ggpubr")
Hitting_Data <- Hitting_Data_EDITED
Hitting_Data


Hitting_P_C <- filter(Hitting_Data_EDITED, Class %in% c("P", "C"))
```


Type introductory paragraph here.


```{r, fig.height=6, fig.width=10}
# create graphic here. Feel free to change fig.height and fig.width, as needed.


# Check correlations (as scatterplots), distribution and print corrleation coefficient
Hitting_Corr <- select(Hitting_P_C,Broad, Vertical, Rotational, EV, Class) #, LA, MVLA, Class)
~~~

~~~
ggpairs(Hitting_Corr, ggplot2::aes(color= Class, alpha=250))
#Look into adding more aesthetics
#ggpairs add trendline
#The more stars, the lower the p value

Hitting_Exp <- filter(Hitting_P_C, Years >= 10)
Hitting_Corr_Exp <- select(Hitting_Exp,Broad, Vertical, Rotational, EV, LA, MVLA, Class)
ggpairs(Hitting_Corr_Exp, ggplot2::aes(color= Class, alpha=250))

Hitting_Nov <- filter(Hitting_P_C, Years < 10)
Hitting_Corr_Nov <- select(Hitting_Nov, Broad, Vertical, Rotational, EV, LA, MVLA, Class)
ggpairs(Hitting_Corr_Nov, ggplot2::aes(color= Class, alpha=250))

#Scratch work
Check1 <- cor(select_if(Hitting_Data, is.numeric), use="complete.obs")
corrplot(Check1)



Hitting_Corr <- select(Hitting_P_C,Broad, Vertical, Rotational, EV)
ggpairs(Hitting_Corr, ggplot2::aes(color= Class, alpha=250))
```


New Correlation Analysis


Check for normality- done using the shapiro test. values above .05 are normally distributed
EV & Rotational
```{r}
#Rotational Medicine Ball Throw
ggscatter(Hitting_Data, x = "EV", y = "Rotational",
        add = "reg.line", conf.int = TRUE,
~~~

```
          cor.coef = TRUE, cor.method = "pearson",
          xlab = "Exit Velocity (mph)", ylab = "Rotational Med Ball Throw (m)",
          color = "blue")
#ggsave(filename = "RMDTvEVcorrfig.jpg")

cor.test(Hitting_Data$EV, Hitting_Data$Rotational, method = c("pearson", "kendall", "spearman"))

shapiro.test(Hitting_Data$EV) # => p = .3487
shapiro.test(Hitting_Data$Rotational) # => p = .05332
#If above .05, we can assume data are normally distributed!!

#Broad Jump
ggscatter(Hitting_Data, x = "EV", y = "Broad",
          add = "reg.line", conf.int = TRUE,
          cor.coef = TRUE, cor.method = "spearman",
          xlab = "Exit Velocity (mph)", ylab = "Broad Jump (m)",
          color= "blue")
#ggsave(filename = "BJvEVcorrfig.jpg")

cor.test(Hitting_Data$EV, Hitting_Data$Broad, method = c("pearson", "kendall", "spearman"))

shapiro.test(Hitting_Data$Broad) # => p = .03908

Broad_cor <- cor.test(Hitting_Data$EV, Hitting_Data$Broad, method= "spearman")
Broad_cor

Broad_cor2 <- cor.test(Hitting_Data$EV, Hitting_Data$Broad, method= "spearman")
Broad_cor2
```

```
#Vertical Jump
ggscatter(Hitting_Data, x = "EV", y = "Vertical",
        add = "reg.line", conf.int = TRUE,
        cor.coef = TRUE, cor.method = "pearson",
        xlab = "Exit Velocity (mph)", ylab = "Vertical Jump (m)",
        color= "red")
#ggsave(filename = "VJvEVcorrfig.jpg")

cor.test(Hitting_Data$EV, Hitting_Data$Vertical, method = c("pearson", "kendall",
"spearman"))

shapiro.test(Hitting_Data$Vertical) # => p = .6143

#t= t-test statistic
#df= degree of freedom
#conf.int = confidence interval
```

POI Coding:

~~~
```{r setup, include=FALSE}
knitr::opts_chunk$set(echo = TRUE)
```{r cars}
library(readr)
library(plot3D)
library(tidyverse)
library(RColorBrewer)
library(readxl)
library(Hmisc)
library(plotly)
library
Top_EV_Data_Exp2 <- read_excel("D:/Kinovea/Top EV Data REAL.xlsx")
~~~

~~~
x <- Top_EV_Data_Exp2$`POI X`
y <- Top_EV_Data_Exp2$`POI Y`
z <- Top_EV_Data_Exp2$`POI Z`
```
```{r}
Top_EV_Data_Exp2 <- Top_EV_Data_Exp2 %>%
  mutate(splitup = paste("", #New Variable, look at package to install for cut2
                         as.numeric(cut2(EV, g=4))))
#EV_cat <- Top_EV_Data_Exp2 %>% mutate(EVc = ifelse(EV))
#Batting_NLCentral <- batting %>% mutate(NLCentral = ifelse(teamID %in%c("MIL", "CIN",
"CHN", "CIN", "PIT"), "Yes", "No")) %>%
 # select(playerID,  yearID, teamID, NLCentral


# plot <- scatter3D(x, y, z, pch = 20,  theta = 20, phi = 20,
#          main = "Point of Impact", xlab = "X Axis",
#          ylab ="Y Axis", zlab = "Z Axis", colvar= NULL, col= Top_EV_Data_Exp2$EV)
# plot + colkey(add = TRUE, clab= "Exit Velocity (mph)", side= 1, clim= (50:75))
# scatter3D(x, y, z, pch = 20,  theta = 5, phi = 20,
#          main = "Point of Impact", xlab = "X Axis",
#          ylab ="Y Axis", zlab = "Z Axis",
#          colvar= NULL, col= Top_EV_Data_Exp2$EV, clab= c("Exit", "Velocity (mph)"))
# scatter3D(x, y, z, bty = "b2", colkey = FALSE, main ="bty= 'b2'") #, color=EV)
#Sketch in a hitter, scale it to a more reasonable
#Code to work with exit velocity
#Rescale to show pitching to bat, not to plate
  ##Explain procedure well, put in methods


Top_EV_Data_Exp2 <- Top_EV_Data_Exp2 %>%
  mutate(splitup = paste("", #New Variable, look at package to install for cut2
                         as.numeric(cut2(EV, g=4))))
~~~

~~~
colors <- c("cyan4", "green", "purple", "red")
colors <- colors[as.numeric(Top_EV_Data_Exp2$splitup)]

ggplot(Top_EV_Data_Exp2, aes(x=`POI Y`, y=`POI Z`)) + geom_point(aes(color=colors))
ggplot(Top_EV_Data_Exp2, aes(x=`POI X`, y=`POI Z`)) + geom_point(aes(color= colors)) + scale_fill_brewer(palette="Accent")
#X is from plate to mound
#Y is side to side

plot <- ggplot(Top_EV_Data_Exp2, aes(x=`POI X`, y=`POI Y`)) +
        geom_point(aes(color= colors)) +
        scale_fill_brewer(palette="Accent")
plot + labs(color = "Exit Velocities")
```
```{r}
library("scatterplot3d") # load
library(readr)
library(plot3D)
library(tidyverse)
library(RColorBrewer)
library(readxl)
library(Hmisc)
library(plotly)
library(moments)
Top_EV_Data_Exp2 <- read_excel("D:/Kinovea/Top EV Data REAL.xlsx")

x <- Top_EV_Data_Exp2$`POI X`
y <- Top_EV_Data_Exp2$`POI Y`
z <- Top_EV_Data_Exp2$`POI Z`
~~~

```
Top_EV_Data_Exp2 <- Top_EV_Data_Exp2 %>%
  mutate(splitup = paste("", #New Variable, look at package to install for cut2
                         as.numeric(cut2(EV, g=4))))

colors <- c("cyan4", "cadetblue1", "violet", "red")
colors <- colors[as.numeric(Top_EV_Data_Exp2$splitup)]
s3d <- scatterplot3d(x, y, z, pch = 16, color=colors,
                     xlab= "Home to Mound (in)",
                     ylab= "Batter's Box to Batter's Box (in)",
                     zlab= "Height of Contact (in)",
                     angle=65, grid= TRUE, box= TRUE)

# plot(NULL ,xaxt='n',yaxt='n',bty='n',ylab=",xlab=", xlim=0:1, ylim=0:1) +
# legend("topleft", legend =c('Below 58.0 mph', '58.0 through 63.5 mph', '63.5 through 65.5
mph',
#     'Over 65.5 mph'), pch=16, pt.cex=3, cex=1.5, bty='n',
#     col = c("cyan4", "cadetblue1", "violet", "red")) +
# mtext("Exit Velocities (mph)", at=0.2, cex=2)
# ggsave(filename = "POIFigure.jpg")

colors <- c("red", "orchid", "slateblue1","cadetblue1", "cyan4")
colors <- colors[as.numeric(Top_EV_Data_Exp2$Rank)]
s3d <- scatterplot3d(x, y, z, pch = 16, color=colors,
                     xlab= "Home to Mound (in)",
                     ylab= "Batter's Box to Batter's Box (in)",
                     zlab= "Height of Contact (in)",
                     angle=65, grid= TRUE, box= TRUE)

plot(NULL ,xaxt='n',yaxt='n',bty='n',ylab=",xlab=", xlim=0:1, ylim=0:1) +
```

~~~~
legend("topleft", legend =c("50.4 - 57.9", "58.4 - 63.3", "63.5 - 65.4", "65.5 - 69.3" ), pch=16,
pt.cex=3, cex=1.5, bty='n',
    col = c("cadetblue1","cyan4","orchid", "red")) +
 mtext("Exit Velocities (mph)", at=0.2, cex=2)
```
```{r}
library(ggplot2)
shapiro.test(Top_EV_Data_Exp2$EV)
  #P-value: .003418
kurtosis(Top_EV_Data_Exp2$EV)
  #2.6288
skewness(Top_EV_Data_Exp2$EV)
  #-.8024497

shapiro.test(Top_EV_Data_Exp2$`POI X`)
  #NOT Normally distributed- CANNOT use parametric tests on them
shapiro.test(Top_EV_Data_Exp2$`POI Y`)
  #Normally distributed
shapiro.test(Top_EV_Data_Exp2$`POI Z`)
  #NOT normally distributed but close: can approximate with the Z point of impact

kurtosis(Top_EV_Data_Exp2$`POI X`)
  #Nope
kurtosis(Top_EV_Data_Exp2$`POI Y`)
kurtosis(Top_EV_Data_Exp2$`POI Z`)

skewness(Top_EV_Data_Exp2$`POI X`)
  #Highly skewed: -2.393085
skewness(Top_EV_Data_Exp2$`POI Y`)
  #"Approximately Symmetric": -.2387732
~~~~

```
skewness(Top_EV_Data_Exp2$`POI Z`)
  #Highly Symmetric: -.03587

#Non-parametric: EV, POI X, POI Z
#Parametric: POI Y
summary(Top_EV_Data_Exp2$EV)
sd(Top_EV_Data_Exp2$EV)
summary(Top_EV_Data_Exp2$`POI X`)
sd(Top_EV_Data_Exp2$`POI X`)
summary(Top_EV_Data_Exp2$`POI Y`)
sd(Top_EV_Data_Exp2$`POI Y`)
summary(Top_EV_Data_Exp2$`POI Z`)
sd(Top_EV_Data_Exp2$`POI Z`)

wilcox.test(Top_EV_Data_Exp2$EV,Top_EV_Data_Exp2$`POI X`, paired=TRUE)
wilcox.test(Top_EV_Data_Exp2$EV,Top_EV_Data_Exp2$`POI Y`, paired=TRUE)
wilcox.test(Top_EV_Data_Exp2$EV,Top_EV_Data_Exp2$`POI Z`, paired=TRUE)

wilcox.test(Top_EV_Data_Exp2$`POI X`,Top_EV_Data_Exp2$`POI Z`, paired=TRUE)
wilcox.test(Top_EV_Data_Exp2$`POI Y`,Top_EV_Data_Exp2$`POI Z`, paired=TRUE)
wilcox.test(Top_EV_Data_Exp2$`POI X`,Top_EV_Data_Exp2$`POI Y`, paired=TRUE)

#ALL medians are different!!
#--> Really interesting because this means a middle middle pitch did NOT produce highest EV
#So what did?

#Box and Whisker Plots first

#MULTIPLE REGRESSION
#EV is the dependent variable
```

~~~
#POI X, Y, Z are the independent variables
#What are the slope values that give you the optimum fit of the equation to the data
#Make a predictive model

#Principle component analysis
#EV as response, weighting functions off of those
d <- density(Top_EV_Data_Exp2$`POI X`)
plot(d)
f <- density(Top_EV_Data_Exp2$`POI Y`)
plot(f)
g <- density(Top_EV_Data_Exp2$`POI Z`)
plot(g)
h <- density(Top_EV_Data_Exp2$EV)
plot(h)
```
```{r}
#MULTIPLE REGRESSION
#EV is the dependent variable
#POI X, Y, Z are the independent variables
#What are the slope values that give you the optimum fit of the equation to the data
#Make a predictive model
model1 <- lm(EV ~ `POI X` + `POI Y` + `POI Z`, data = Top_EV_Data_Exp2)
summary(model1)

ggplot(Top_EV_Data_Exp2, aes(x=splitup, y= `POI X`)) +
  geom_boxplot(aes(fill=splitup)) +
  xlab("Exit Velocity Tier")+
  ylab("Point of Impact X (in)") +
    scale_fill_discrete(name= "Exit Velocity (mph)",
                      labels= c("50.4 - 57.9", "58.4 - 63.3", "63.5 - 65.4", "65.5 - 69.3")) +
~~~

```
  theme(legend.position="right")
ggplot(Top_EV_Data_Exp2, aes(x=splitup, y= `POI Y`)) +
  geom_boxplot(aes(fill=splitup)) +
  xlab("Exit Velocity Tier")+
  ylab("Point of Impact Y (in)") +
    scale_fill_discrete(name= "Exit Velocity (mph)",
                        labels= c("50.4 - 57.9", "58.4 - 63.3", "63.5 - 65.4", "65.5 - 69.3")) +
  theme(legend.position="right")



ggplot(Top_EV_Data_Exp2, aes(x=splitup, y= `POI Z`)) +
  geom_boxplot(aes(fill=splitup)) +
  xlab("Exit Velocity Tier") +
  ylab("Point of Impact Z (in)") +
    scale_fill_discrete(name= "Exit Velocity (mph)",
                        labels= c("50.4 - 57.9", "58.4 - 63.3", "63.5 - 65.4", "65.5 - 69.3")) +
  theme(legend.position="right")

median(Top_EV_Data_Exp2$EV)
```