An Experimental Comparison of Hitting Mechanics in Softball

by

Tori Jensen

Submitted to the Department of Mechanical Engineering
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Signature of Author: Signature redacted ....
Department of Mechanical Engineering

Certified by: .... Signature redacted ...
Dawn Wendell, PhD
Senior Lecturer
Thesis Supervisor

Certified by: .... Signature redacted .....
Anette (Peko) Hosoi, PhD
Professor of Mechanical Engineering
Undergraduate Officer

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ABSTRACT

To score points to win games, a softball team must be able to hit the ball with as the largest velocity as possible. In softball, there are two well-known hitting models, rotational and linear, yet little quantitative research has been done to determine which model produces the greatest ball velocity and if certain key inputs, such as weight shift and bat velocity, of the models contribute to that velocity. To determine these components, a high-speed EXLIM camera recorded the change in ball position to calculate the its exit velocity, a 70g accelerometer measured centripetal acceleration of the bat to determine bat velocity, while two force plates measured the transfer of weight as nine softball players swung a bat twenty times- ten times with a ball on the tee and ten times with a ball off of the tee. Although it was found that the two hitting models had statistically different weight shifts with 95% confidence, the average ball velocity for a linear model, 22.0 m/s ± 1.9 m/s, was not different from the average ball velocity for a rotational model, 22.0 m/s ± 0.7 m/s, at 95% confidence. Since these values are not different with statistical significance, this research concludes that players that weight shift does not effect ball velocity and that players are encouraged to use whichever model feels most comfortable to them.

Thesis Supervisor: Dr. Dawn Wendell, PhD

Tile: Senior Lecturer

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1. Introduction

Without a doubt, sports are an important aspect of American culture. From participating to watching, sports are ingrained in American society from the time of childhood. Three out of four families with school-age children have at least one child participating in an organized sport [1]. By the time of high school, there are 7.8 million High School athletes in the United States [2]. In addition to millions of Americans playing sports, millions more are watching sports, which makes sports coverage lucrative for the media. *ESPN*, a main sports network for American TV viewers, earned 10.8 billion dollars in 2014 [3].

In terms of baseball and softball, these sports are of great popularity in the United States. Baseball, which is known by its old slogan of America's past time, has a yearly attendance of 74.2 million fans at Major League Baseball (MLB) games, along with an additional 2-5 million viewers per day on television [4]. Although there is not as much clear data for softball since there is not a mainstream professional softball team yet, it is clear that softball is picking up more popularity as there were over 2 million viewers for the college softball finals in 2015, which was more than the number of viewers for the college baseball finals [5]. Since it is clear that these sports are favorites in the United States, it is crucial to next examine why this is and what part of these sports keeps people both playing and watching them.

Besides the peanuts and crackerjacks, these games keep fans on the edge of their seats because they are always waiting for the next big hit. Although fans expect to see a show, from the player perspective, an enormous amount of training goes into being able to hit the ball consistently far. However, for decades in the realm of softball and baseball, there has been a great debate in the philosophy of hitting and how a player can get the most "power" – or in other words, hit the ball to their fullest potential. This debate centers around two hitting methods (more commonly referred to as hitting models), called linear and rotational models. Although the fine points regarding the definitions for linear and rotational models are still argued about, most professionals can agree on the following basic criteria to distinguish between the two hitting models. A linear model emphasizes hitters to generate a quick swing by moving their hands straight to the ball and shifting their weight to the front foot. In Major League Baseball, famous linear hitters include Ichiro Suzuki and Derek Jeter [6]. Meanwhile, a rotational model teaches batters to minimal shift forward and instead produce a fast angular velocity trough rotation about a stationary axis. Famous rotational hitters include Albert Pujols and Andres Torres [6]. Although the majority of baseball hitters use a rotational model, both models are common in softball.

Even though these models have been around for decades, very little quantitative research has been done to examine the effectiveness and components of each model [7]. In the field of softball research, most studies tend to examine ball velocity or bat properties, and therefore there is a lack in research in the actual swing mechanics. This paper aims to observe which model produces the greatest exit ball velocity by measuring the weight shift, bat velocity, and ball velocity of both linear and rotational hitters and comparing the components of each model to one another. This paper also attempts to observe how bat velocity correlates to ball velocity, and aims extend the previous research done by Lloyd Smith in this area [7]. Results from this data could potentially improve existing baseball and softball swing models, as well as determine if there is an optimal model to use. This data will be collected by measuring the ball velocity of a given swing with a Casio EXLIM high-speed camera, by measuring the bat velocity with a Vernier 70g accelerometer, and by measuring the weight shift of a player's swing through having the player stand on two force plates.

2. Background

This section gives a brief overview of both the history and rules of softball, as well as the underlying physical principles of the two hitting models and the basic physics of hitting a ball in general.

2.1 Brief Background of the History and Rules of Softball

Created in 1887 in Chicago, softball was originally advertised as an indoor game for baseball players wanting to maintain their skills during the offseason [8]. However by 1895, it had turned into an outdoor game of its own and in 1933, the first ever national amateur softball tournament took place. Today, it is estimated that nearly 40 million Americans, both men and women, engage in at least one softball game each year, with players ranging from 5 years old to over 60 years old [8]. Globally, 113 countries have joined the International Softball foundation since it's foundation in 1952 [8]. Although collegiately and more commonly, softball is now considered a women's sport, with colleges in the United States championing 1,673 teams with 30,469 players, men of all ages participate in leagues as well [9].

Softball is similar to baseball, with a few notable differences. The greatest differences between the two sports is that in softball, the ball is pitched underhand, rather than overhand, the field dimensions are smaller, and the ball is larger. However, the gameplay itself is nearly identical to baseball. Like baseball, softball is played in a series of innings where the two teams rotate playing defense and offense in each of the innings. On defense, nine players take the field, as shown in Figure 1, and try to get hitters on the opposing team out by either catching a ball hit in the air, striking a player out at the plate, or fielding a ball on the ground and throwing it to the base before the batter reaches it. On offense, one player at a time tries to hit a ball thrown to them by the pitcher in fair territory and get on base to try to score a point. A point is scored once the hitter rounds all four bases. Usually this is done sequentially, with multiple batters hitting the ball to advance their teammate to the next base. The objective of the game is to have scored the most points by the end of the game.

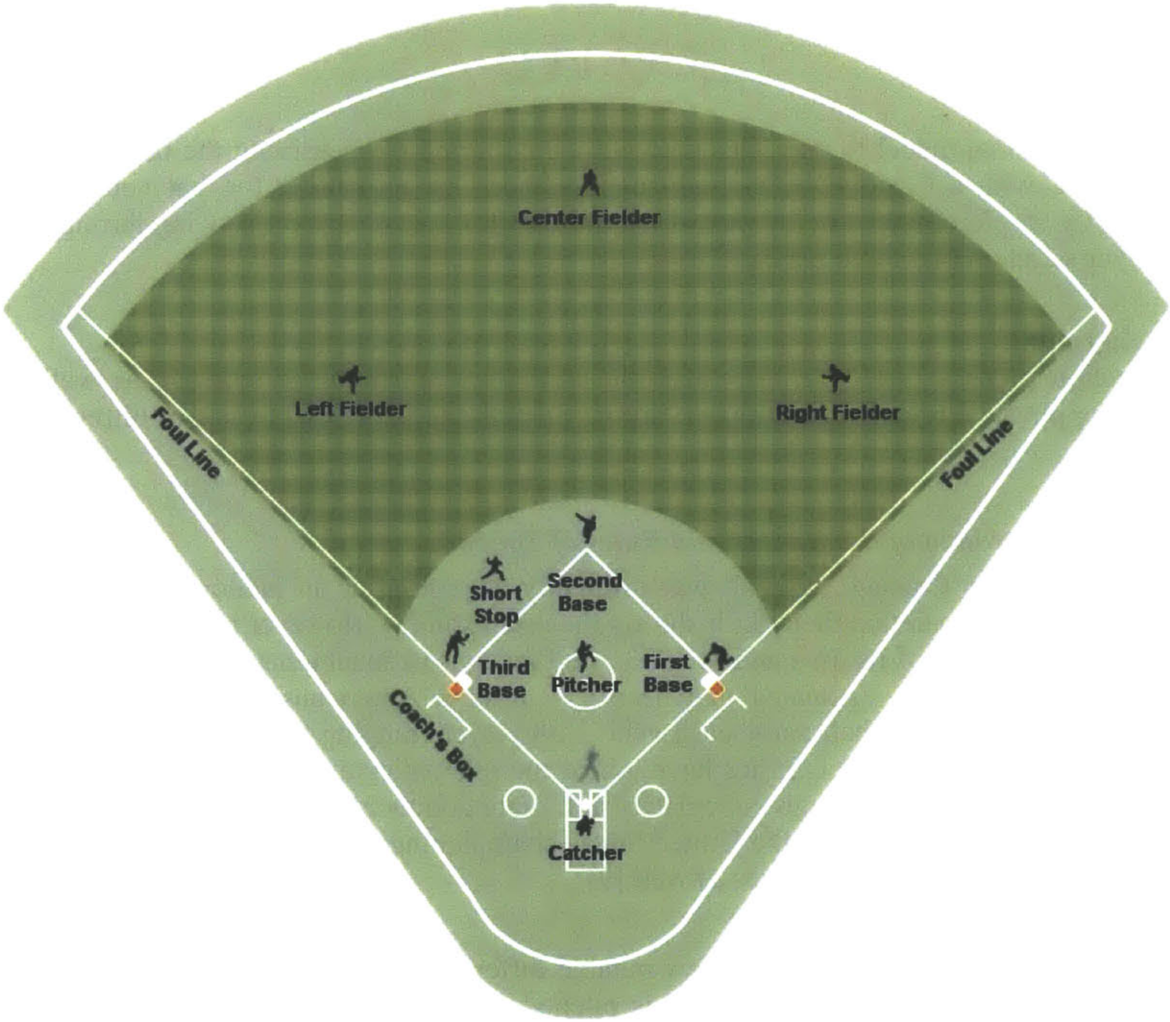

Figure 1: A simple diagram depicts a typical softball field, as well as the position of the nine defensive players [10].

Therefore, to be able to win games, teams must have players who can hit the ball with great velocity so that the team can score more points than their opponent. Because of this, there is a large emphasis on teaching hitting mechanics that will produce the greatest ball velocity. However it should be noted, this is not always the case, since there are special circumstances where players do not want to hit the ball with a large ball velocity, such in the case of slap hitters. For slap hitters, their goal is to hit the ball into the ground at a slow enough speed so that they can run to first before the fielders have time to throw them out at first.

In this experiment, large ball velocity was consciously chosen as the desirable outcome of a swing by the researcher, but as stated before, this is not always the desirable outcome in a game situation or for a certain kind of hitter. If this study were focusing on slap hitters, ball angle and low ball velocity would be the desirable outcome.

It should be noted that until this research, there has been no quantitative data to back up which model, if any, produces the greatest ball velocity. This research will improve the softball community's understanding of the two most prominent hitting models, linear and rotational, and give a quantitative analysis on which model, if any, should be taught to players to increase ball velocity.

2.2 Definition of a Linear Model

Most will agree upon the following basic criteria for a linear hitting model. As shown in Figure 2, a linear hitting model is one which emphasizes batters to generate a quick swing by moving their hands in a straight path down to the ball while shifting their weight forward at the same time [6]. In this model, the batters' hands move first and her hips do not rotate until the end of the swing.

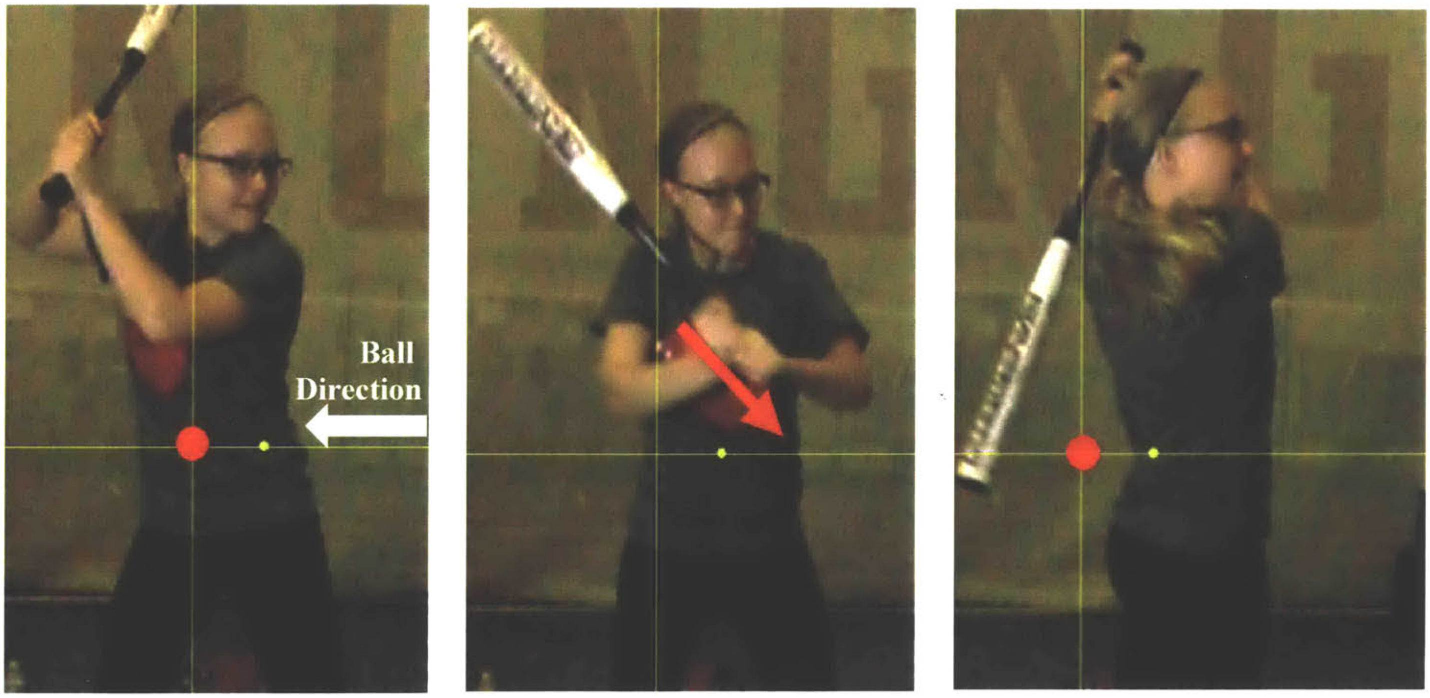

Figure 2: These three photos illustrate the dramatic weight shift forward during a swing in the linear hitting model, in addition to depicting the downward linear path of the bat. As shown, the hitter moves linearly forward from her original position as marked by the red dot.

This hitting model attempts to generate large ball velocity through a translational change in momentum of the body in addition to a rotational swing of the bat at the very end. The diagram in Figure 3 is a top view of the swing before the ball is hit and after the ball is hit for the linear model. In this diagram, M_h is the mass of the hitter, v_{h1} is the translational velocity of the hitter, m_B is the mass of the bat, m_b is the mass of the ball, v_{b1} is the initial velocity of the ball v_{B1} is the initial tangential velocity of the bat, v_{B2} is the final tangential velocity of the bat, and v_{b2} as the final velocity of the ball.

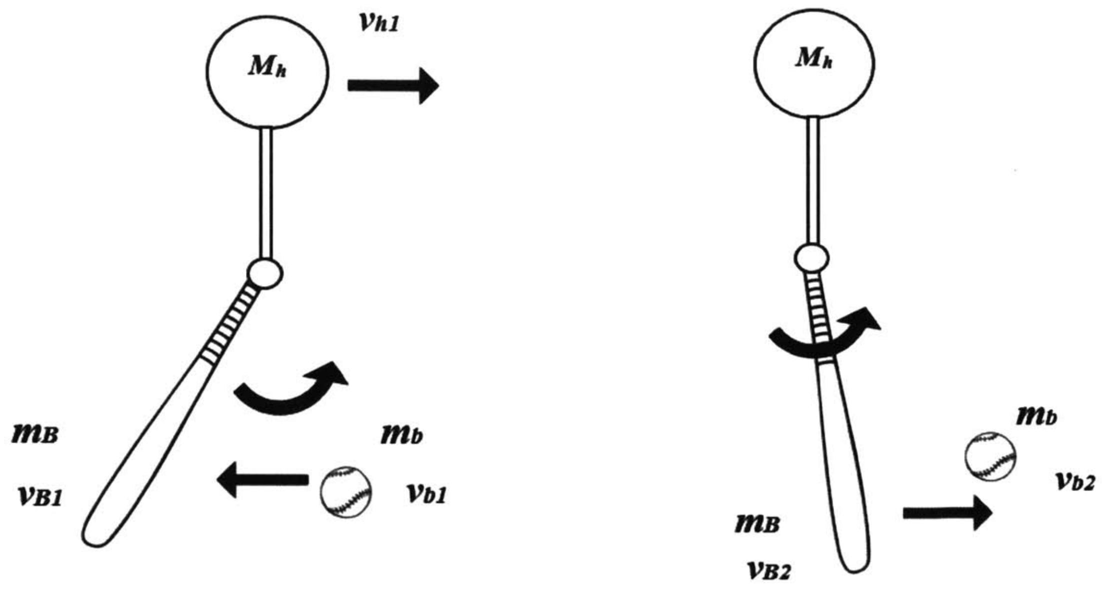

Figure 3: This diagram depicts the top view of a linear swing, with M_h as the mass of the hitter, v_{h1} as the translational velocity of the hitter, m_B as the mass of the bat, m_b as the mass of the ball, v_{b1} as the initial velocity of the ball v_{B1} as the initial tangential velocity of the bat, v_{B2} as the final tangential velocity of the bat, and v_{b2} as the final velocity of the ball [11].

The underlying physics which governs this motion to produce a large final ball velocity is the change in momentum and the law of conservation of momentum. In a linear swing, momentum is being transferred to the ball in two parts. The first is from the linear movement of the batter herself, where her momentum is defined her initial velocity times her mass. Therefore, the larger translational shift forward, the greater change in momentum and the greater ball speed. This is related to the weight shift of the player since the weight shift forward occurs due to a force, and this force produces an acceleration which increases the velocity of the batter forward.

The second component of momentum which is transferred from the hitter to the ball is from the angular motion of the bat. This is called angular momentum, and it is defined as

$$L = I\omega, \tag{1}$$

where L is angular momentum, I is moment of inertia, and ω is angular velocity. As shown in Figure 4, angular velocity is also related to tangential velocity by angular velocity by multiplying angular velocity by the radius, in this case, the bat length. Thus, the larger the angular velocity is, the larger the translational velocity and the larger the ball velocity. The argument for the effectiveness of the linear model centers on the fact that the change in momentum is coming from two sources. The two sources are translational momentum from the hitter's weight shift and angular momentum from the bat. It is argued that together these two sources of momentum can produce a larger ball velocity than if there was only one source of momentum from the bat.

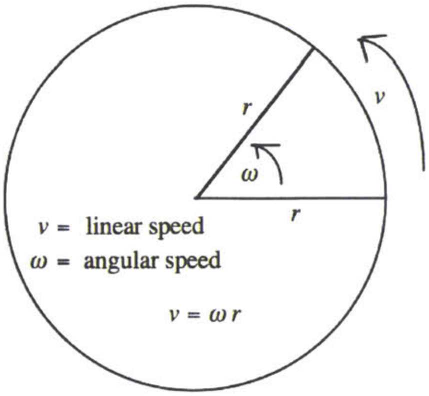

Figure 4: This figure illustrates the relationship between angular velocity and tangential velocity [12]. As shown, tangential velocity is angular velocity multiplied by the radius of the circle. In this experiment, velocity of the bat is the tangential velocity.

2.3 Definition of a Rotational Model

Contrary to the linear hitting model, the rotational hitting model teaches players to turn their hips first to make their bat barrel rotate with a high angular velocity around their own stationary axis. Although weight shifting occurs in every hitting model, the rotational hitting model aims to minimizes this, and focus on producing high angular velocity through rotational movement, as shown in Figure 5.

Figure 5: This image depicts a swing following a rotational model. Instead of moving straight to the ball, the barrel of the bat rotates around a stationary axis at a fast angular velocity. Note that the player's bat barrel is flat, not angled downward, and rotating around her own stationary axis. In addition to this, her hips are also turning to generate a high angular velocity [13].

This hitting model generates high ball velocity through a high angular velocity. The diagram in Figure 6 is a top view of the swing before the ball is hit and after the ball is hit for the rotational model. In this diagram, M_h is the mass of the hitter, m_B is the mass of the bat, m_b is the mass of the ball, v_{b1} is the initial velocity of the ball v_{B1} is the initial tangential velocity of the bat, v_{B2} is the final tangential velocity of the bat, and v_{b2} as the final velocity of the ball.

Unlike the linear model which benefits from two sources of momentum change, translational weight shift and angular momentum from the bat, the rotational model only benefits from the angular momentum of the bat. However, proponents of the rotational swing argue that this model can provide just as much bat velocity as a linear model even though it does not benefit from translational change in momentum. It is thought that because rotational hitters do not shift their weight forward, they can utilize that "extra" force in producing high torque, since torque is force times distance, when swinging the bat. The total torque produced is related to angular acceleration in the following way,

$$\sum\tau = I\alpha, \tag{2}$$

where τ is torque, I is moment of inertia, and α is angular acceleration. Therefore, because more torque is produced in this model, a greater angular acceleration can be obtained, which means a greater angular and tangential velocity will be produced, and thus will generate a larger ball velocity due to conservation of momentum.

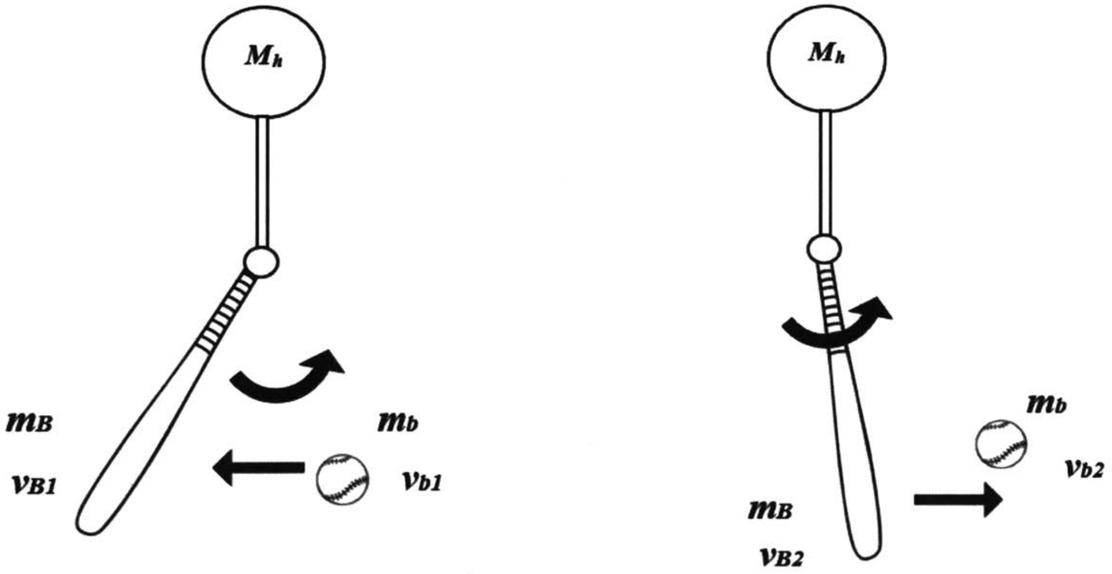

Figure 6: This diagram depicts the top view of a rotational swing, with M_h as the mass of the hitter, m_B as the mass of the bat, m_b as the mass of the ball, v_{b1} as the initial velocity of the ball v_{B1} as the initial tangential velocity of the bat, v_{B2} as the final tangential velocity of the bat, and v_{b2} as the final velocity of the ball [11].

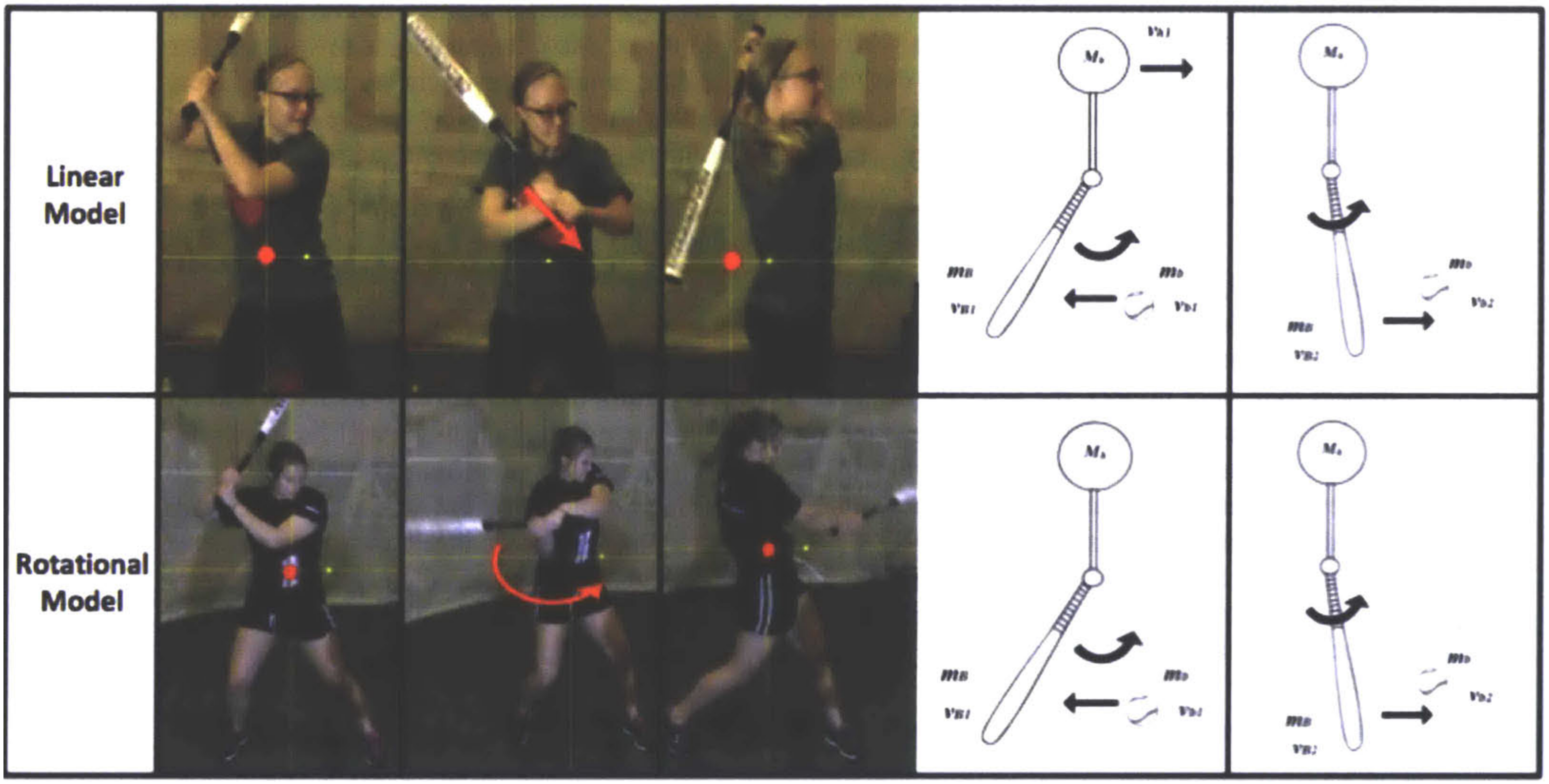

Figure 7: This figure show summarizes two models, rotational and linear, side by side in order to emphasis the differences in the hitting mechanics of each swing. As stated before, the linear model emphasizes weight shift forward as well as moving your hands in a direct path to the ball. On the other hand, the rotational model emphasizes rotating your bat around your body quickly, while keeping your body still to provide a stationary axis to rotate around.

In conclusion, Figure 7 summarizes the differences in the two hitting models. Although there are more subtle differences between the two models, the most important differences are in weight shift and the hand path to the ball. Thus, for this experiment, a large focus was put on observing differences in weight shift since this was the most distinguishing component of the two hitting models.

2.4 Velocity of a Batted Ball

Previous research has found that there is a positive linear correlation between bat velocity and ball velocity [7]. The explanation for this finding was that ball velocity was only dependent on bat velocity and bat properties since these two elements were the most immediate sources of momentum transfer [7]. This research, therefore, did not include weight shift of the hitter in their calculations, but noted that it could be done in future work. The correlation between bat velocity and ball velocity that was found by this research group can be defined by the following relationship,

$$v_h = e_a v_p + (1 + e_a) v_s, \tag{3}$$

where v_h is the ball velocity, v_s is the bat velocity, v_p is the velocity of the ball pitched, and e_a is the collision efficiency of the bat. In the case of the experiment presented in this paper, v_p is zero since the batters are hitting a stationary ball off of a tee. Also, because e_a is always greater than 1, this means the function that is derived from the data in this experiment should be a linear correlation with a slope greater than 1. This also means that the velocity of the ball should always be greater than the velocity of the bat, which is in agreement with momentum conservation,

$$m_{bat} v_{bat,1} = m_{bat} v_{bat,2} + m_{ball} v_{ball}, \tag{4}$$

where m_{bat} is the mass of the bat, $v_{bat,1}$ is the velocity of the bat before impact, $v_{bat,2}$ is the velocity of the bat after impact, and v_{ball} is the velocity of the ball. Since the mass of the bat is always greater than the mass of the ball, and because the velocity of the bat is greater before impact than after impact, the velocity of the ball will be greater than the initial velocity of the bat for head on collisions. These equations and the physical reasons behind them will be important when comparing the measured bat velocity to the measured ball velocity. It should be noted however, that the research group who found the relationship between bat and ball velocity in Equation 3 had hitters swing off of a live pitcher, not a tee. This introduces a large amount of variability in their calculations, which is not present in the presented paper since the ball velocity begins at 0 m/s. This may be a reason for any noticeable differences in observed bat and ball velocity correlations between these two studies.

3. Experimental Design to Determine Bat Velocity, Ball Velocity, and Batter Weight Shift

Contrary to previous studies, which have broken up similar experiments into two set ups to record weight shift and bat and ball velocity independently [14], this study used only one set up in order to record all components simultaneously. The reason for this was so that each swing could be compared holistically in terms of weight shift, bat velocity, and ball swing, and if these components depended on one another. Inspired by previous studies [7, 15], in this experiment, a Casio EXLIM high speed camera[1] was used at 1000 frames/second to determine ball speed. At the same time, two Vernier force plates[2] were utilized to measure the change in force between a hitter's bat leg and a front leg during a swing. This measures the batter's weight shift forward when hitting. To record bat velocity, an Analog Devices 70g accelerometer[3] was attached to the end of the bat, which measured the centripetal acceleration of the bat, and could be in turn used to calculate the tangential velocity of the bat.

3.1 Apparatus

In this part of the experiment, nine right-handed MIT Varsity Softball players took a total of twenty swings each - ten swings with a ball on a tee, and ten swings with no ball on a tee. The same ball, a standard 0.3 m diameter NCAA softball, was used in every experiment, as well as the same bat, a 2013 Easton Stealth Bat with a length of 0.84 meters and a mass of 0.94

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[1] http://www.casio-intl.com/asia-mea/en/dc/ex_100/

[2] http://www.vernier.com/products/sensors/force-sensors/fp-bta/

[3] http://www.analog.com/en/products/mems/mems-accelerometers/adxl001.html#product-overview

kilograms. The height of the tee was controlled for each experiment at 0.14 meters below the navel of each player. Unlike previous experiments that use the same tee height for every player, this experiment set the tee height relative to the navel of the player so that they would all be hitting the same pitch location in relation to their height in order to standardize the hitting of each player [14]. Each batter stood 0.56 m away from the tee and placed their each foot on a Vernier force plate which were 0.28 m apart. Every time a batter would swing, a video was recorded of their swing with the Casio EXLIM high-speed camera at 1,000 frames/second and their weight shift was recorded by the force plates that they stood on. These force plates were connected to a Vernier LabQuest Mini[4], which displayed the change in force in Newtons on the LoggerPro interface. This setup can be further depicted in Figure 8.

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[4] http://www.vernier.com/products/interfaces/lq-mini/

Figure 8: This diagram displays the setup used to determine the weight shift, the bat velocity and the ball velocity. As shown, the batter is hitting a ball off of a tee, while being filmed by a Casio EXLIM high-speed camera at 1,000 frames/second. The LED floodlight provides lighting to obtain better video quality. Simultaneously, the player stands on two force plates, and the force applied to each plate during the swing is recorded through the LabQuest Mini and LoggerPro. A Vernier 70g accelerometer is attached to the end of the 2013 Easton Stealth bat to record the centripetal acceleration.

3.2 Methods of Determining Weight Shift, Bat Velocity, and Ball Velocity

3.2.1 Determining Weight Shift

The data was recorded by zeroing the instruments before the batter stepped onto the force plate. When the batter stepped on the force plates, this triggered LoggerPro to begin recording the force of the batter on each foot. Once on the force plates, the batter waited 2 seconds, loaded, waited 2 more seconds, and then swung the bat. This procedure was used in order to obtain a complete view of the batter's weight shift before, during, and after a swing. Unlike other previous research which zeroed sensors once the batter was in a loaded position, this experiment was able to gain insight into how the batter distributed their own weight prior to their loaded position, how much weight they loaded backwards right before their swing, and how much weight they shifted forward during and after their swing. Previous research was only able to record weight shift during and after the swing.

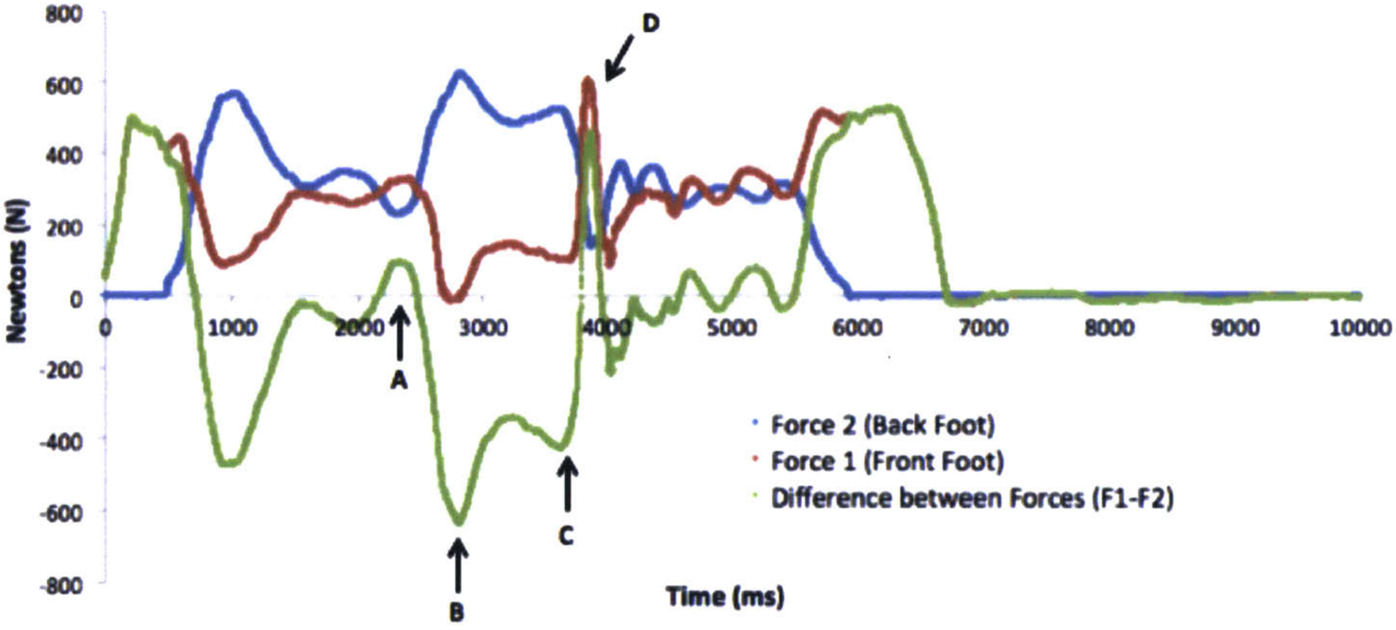

Figure 9: This graph shows the raw data of the force collected on the two force plates by the LoggerPro as a player swings, as well as the calculated difference between the forces. The difference between the force on the front foot and the force on the back foot gives the change (or shift) of the force between the batter's two feet as a function of time. The labeled local minima and maxima of the green line highlight key aspects in the batter's swing: **A)** This local maximum indicates a net force to the front foot, as a trigger before the batter goes into their load backward; **B)** This local minimum indicates the batter's initial loaded position with a net force to the back foot; **C)** This local minimum indicates the batter's loaded position right before their weight shift forward – note the magnitude is less than point B, which means that there is not as much weight shift back as initially intended by the batter; **D)** This local maximum indicates the weight shift forward to the front foot during the swing. This is the only point that is further analyzed in this paper since the rotational and linear models are solely concerned with weight shift forward.

As shown by the graph in Figure 9, the maximum value of the difference between Force 1 and Force 2 at point D is the weight shift forward (N) of the batter during their swing. Due to the fact that players vary in weight and therefore have a different amount of weight available to shift forward, it is crucial that the weight shift forward is quantified in terms of the percent of the batter's weight, rather than in Newtons (N). The percent of weight shift forward during a swing can be calculated by the following formula

$$Percent\ of\ Weight\ Shift\ Forward\ (\%) = \frac{Maximum\ Weight\ Shift\ Forward\ (N)}{Average\ Weight\ of\ Batter\ (N)} \times 100, \qquad (5)$$

where the average weight of the batter (N) is calculated by summing the values from both force plates at each point in time and then dividing by the total number of data points. It should be noted that due to this averaging method, it is possible to obtain a percent of weight shift forward slightly greater than 100%.

3.2.2 Determining Bat Velocity

During the experiment, the 70 g accelerometer, which was attached to the end of the bat, measured the centripetal acceleration of the bat. This can be used to calculate the tangential velocity of the bat through the equation

$$a_c = \frac{v_t^2}{r}, \qquad (5)$$

where a_c is the centripetal acceleration (m/s^2) collected from the accelerometer as shown in Figure 10, r is the radius (m), which in this case in the length of the bat (0.84 m), and v_t is the tangential velocity of the bat.

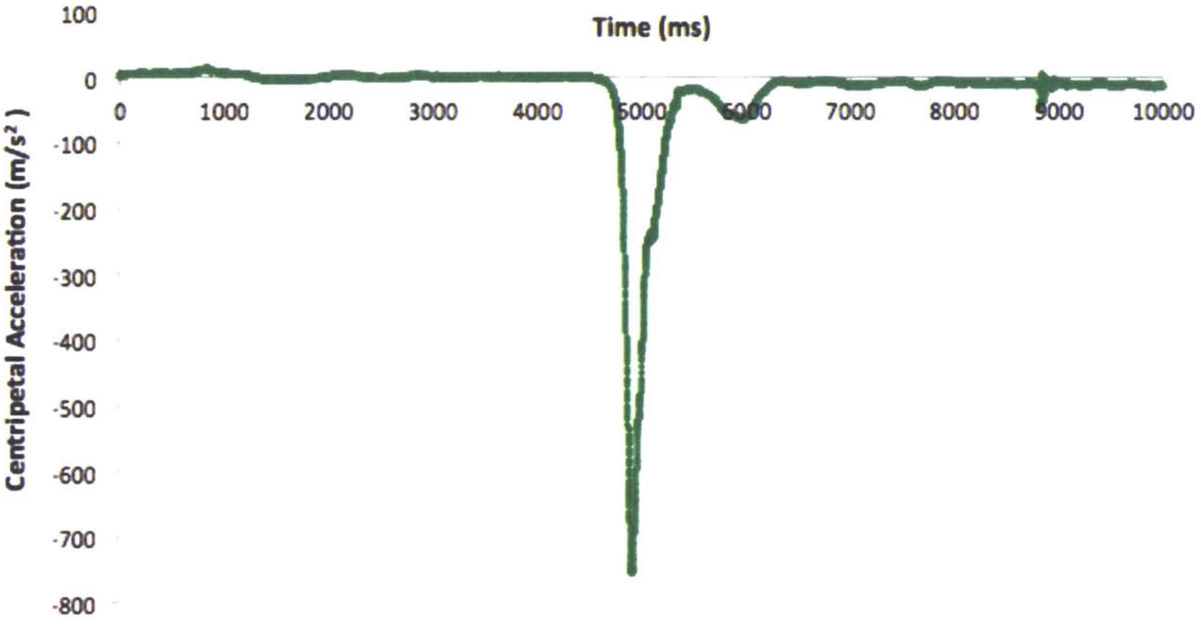

Figure 10: This graph shows the raw data of the centripetal acceleration recorded by the 70g accelerometer at a sample rate of 1000 samples/second. This accelerometer attached to the end of the 0.84 m Easton Stealth bat and the centripetal acceleration measured can be used to calculate the tangential velocity of the bat.

3.2.3 Determining Ball Velocity

The videos recorded by the high-speed EXLIM camera were analyzed in LoggerPro and the ball velocity was determined by plotting the distance the ball traveled within a frame against the time elapsed during that frame. The line of best fit on this graph, as shown in Figure 12, is the average ball velocity for that given swing.

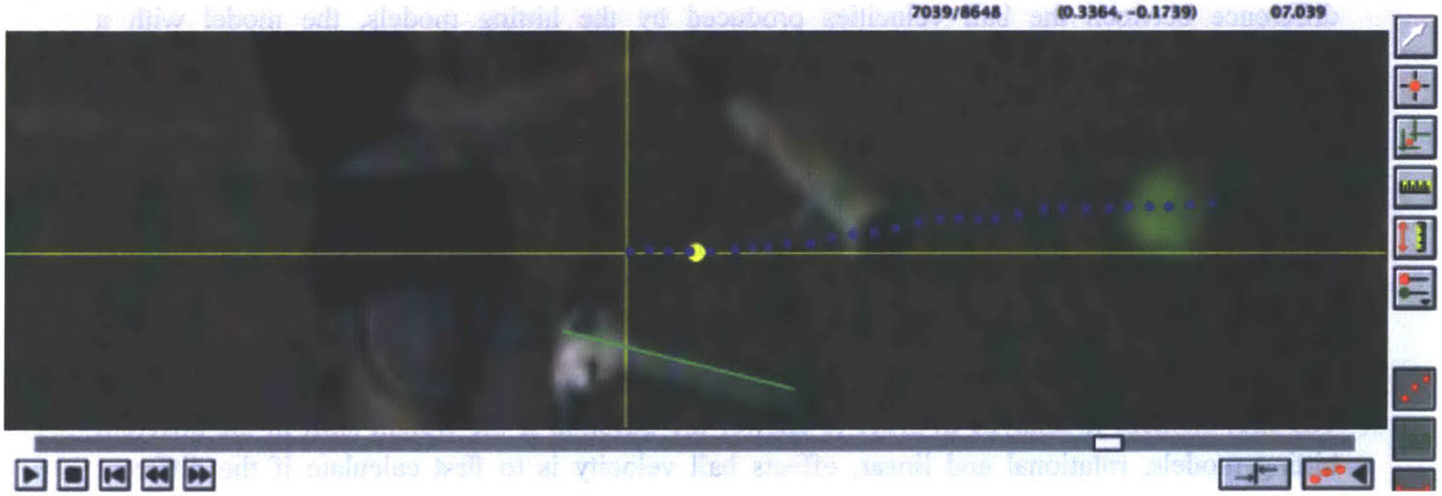

Figure 11: This screenshot depicts the procedure for obtaining position of the ball in meters by marking the ball's position in each frame with blue dots, and then setting the scale (green line) equal to the distance of the ruler. This allows LoggerPro to calculate the distance traveled by the ball in the video because it now has a relationship between pixels and meters.

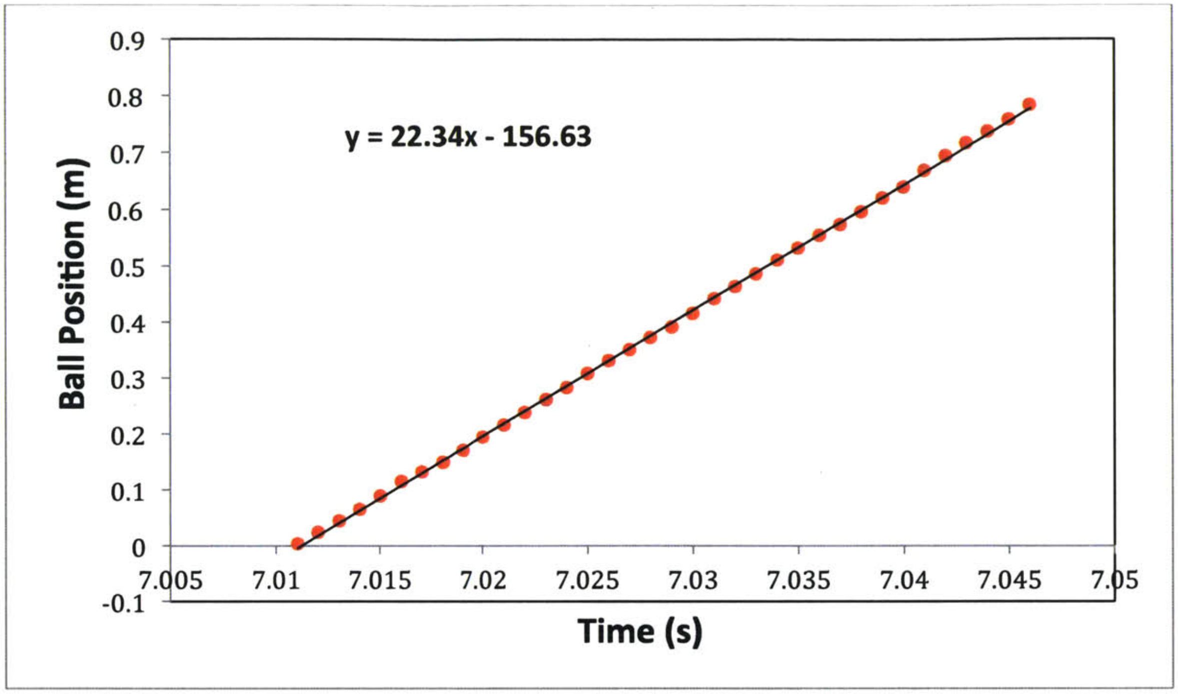

Figure 12: This graph shows the position vs time plot of ball during a hit. From this graph, the line of best fit can be calculated and the slope of this line gives the average ball velocity for the given hit. For this particular hit, the ball velocity is 22.34 m/s.

4. Results and Discussion

The main goal of this experiment was to determine which hitting model, as defined by the weight shift forward, was "better" as measured by the ball velocity. If the data showed a significant difference between the ball velocities produced by the hitting models, the model with a significantly greater ball velocity would be the desirable model for future power hitters to follow.

If the weight shift did affect the ball velocity, another goal of the experiment was to observe if players could accurately self-identify which hitting model they followed, and how training could be improved if this feedback on weight shift was needed. Although this paper may focus heavily on weight shift in order to distinguish between a linear and rotational swing, this paper is primarily concerned with identifying key components that will increase exit ball velocity and how softball players should train in the future to do so.

4.1 Linear and Rotational Weight Shift

The first element to analyze in order to answer the question if the weight shift in the different hitting models, rotational and linear, effects ball velocity is to first calculate if the different hitting models have statistically significantly different weight shifts. This is important because if the batters who used rotational and linear models do not have statistically significantly different weight shift, then this would mean that in general, batter's shift their weight forward relatively the same amount and therefore it is not a defining characteristic of the swing or the model they choose to use.

In this experiment, it was defined that if a batter shifted less than 50% of their weight forward, they were considered a rotational hitter, while if they shifted more than 50% of their weight forward, they were considered a linear hitter. As shown in Figure 13, based solely on the percent of their weight shift forward, there were five hitters who were categorized as linear hitters and four hitters who were categorized as rotational. Given this breakdown of rotational and linear hitters, it was found that rotational hitters shift 22.5% ± 11.0% of their weight forward on average, while linear hitters shift 75.8% ± 20.7% of their weight forward on average. When a t-test was applied to these data sets, it was shown that the percent weight shift forward of these models were statistically significantly different with 95% confidence. This means that the weight shift forward of these models is a unique and defining characteristic of the model.

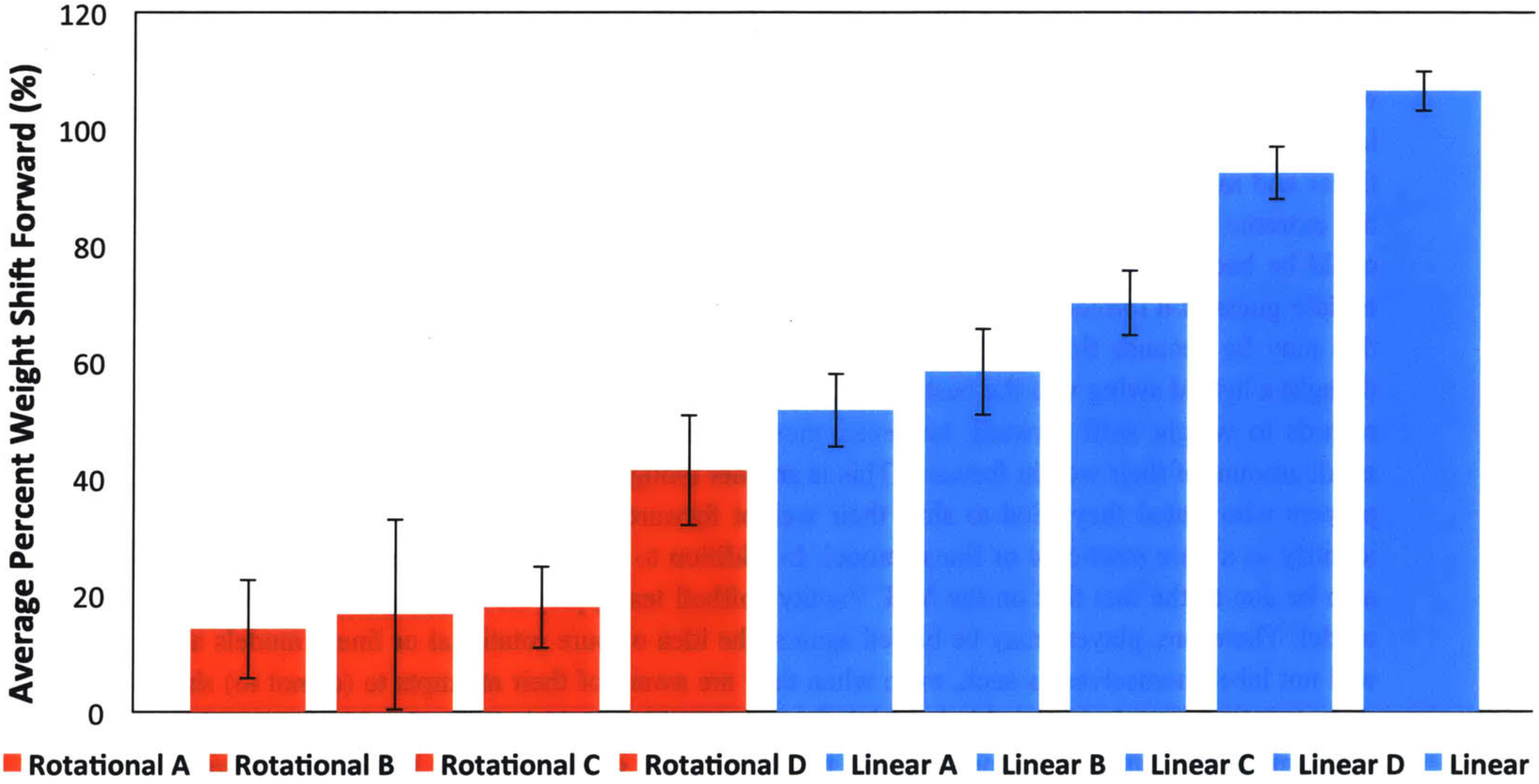

Figure 13: These graph shows the distribution of percent weight shift among the nine players. Those who had less than a 50% weight shift forward, were categorized as a rotational hitters (red), while those who had greater than a 50% weight shift forward were categorized as linear hitters (blue).

Now that it has been quantitatively determined that these two models are different in their percent weight shift forward, the next step of the analysis is to see if batter's are able to identify which model they follow and if they believe they try to shift their weight forward. It is important to look at this self-identification component of the swing analysis because this is a huge factor in the training aspect of softball. If players are following different hitting models, but are unable to identify that in their hitting mechanics or believe they are doing the opposite of what they're actually doing, then they will not be successful in their swing.

For this part of the analysis, both a qualitative and quantitative approach was taken. Each approach offers its own insights on players' hitting mechanics, and when combined, provide a more holistic understanding of these hitting models.

Qualitatively, each player in the study was asked four questions: what (if any) hitting model were they taught when they were younger (before age 14), what model (if any) do they identify with now, do they consciously try to shift their weight forward during a swing, and what hitting model do they think is best (i.e. produces the greatest ball velocity). As shown by Table 1, the player responses yield some interesting results. The first is that although 6 out of 9 players' current hitting model matched what they were taught at a young age, only 1 out of the 9 players was able to correctly identify which model they followed. This may indicate that what players were taught at a younger age correlates more with what they actually do then what the players try to do or what they think they do now. Another interesting observation was the reluctance of players to identify with either model. The majority of players identified as having a combination of both a linear and model swing, or in other word, a hybrid swing. Even in cases where a player was on the extreme end of the rotational-linear swing spectrum, they would identify as hybrid. This could be because players did not want to guess incorrectly about their swing and took a safe middle guess at it (which indicates again, that a player is only *guessing* what they are doing). Or this may be because this is what a player *wishes* they were doing since almost every player thought a hybrid swing was the best model, and therefore is trying to emulate it. On responses in regards to weight shift forward, however, most players knew if they were shifting a large or small amount of their weight forward. This is another thought-provoking point since even though players who stated they tried to shift their weight forward were correct, they still hesitated to identify as a pure rotational or linear model. In addition to reasons already discussed, this could also be due to the fact that on the MIT Varsity softball team, players are taught a hybrid swing model. Therefore, players may be biased against the idea of pure rotational or linear models and will not label themselves as such, even when they are aware of their attempts to (or not to) shift their weight forward. Again, this is insightful because this would indicate that players see their mechanics being influenced more by the model they are currently being taught, but it would seem from this small sample data, that what players were taught when they were younger is more influential to how they swing currently. Since this is a small set of data, more experiments with a larger amount of players is required to confirm or deny these speculations. However, this data serves the purpose of highlighting critical questions of how players view their own hitting mechanics since this type of reflection is crucial for training and improvement in the sport.

Table 1: This table portrays subjects' responses to interview questions regarding which model they were taught, which model they identify their swing with today, if they consciously try to shift their weight forward, and what model they think is "best" (i.e. produces the greatest exit ball velocity). The subjects listed in the left-column are listed by percent weight shift forward, meaning Rotational A hitter shifted the least amount of their weight forward, while Linear E player shifted the most weight of their weight forward. For a more visual representation of this distribution, see Figure 12.

Experimental Identification	Taught	Self-Identification	Tries to Shift Weight	Best Model
Rotational A	Rotational	Linear	No	Hybrid
Rotational B	Rotational	Hybrid	Yes	Hybrid
Rotational C	Rotational	Hybrid	No	Hybrid
Rotational D	Rotational	Hybrid	No	Hybrid
Linear A	Linear	Hybrid	Yes	Hybrid
Linear B	Rotational	Linear	Yes	Linear
Linear C	Hybrid	Hybrid	Yes	Hybrid
Linear D	Hybrid	Hybrid	Yes	Hybrid
Linear E	Linear	Hybrid	No	Hybrid

Once these responses were recorded, a more quantitative approach could be taken with the data collected regarding the percent of weight shift forward. Instead of dividing the labels of rotational and linear models based on whether the player shifted their forward by less than or more than 50%, it can now be divided based on what hitting model the players identified their swings as. As shown by Figure 14, there is a clear difference between when players are categorized by what model they self-identify as and what they actually followed. As stated before and shown in Figure 14a, when classified by the sheer percentage of their weight shift forward, rotational hitters shifted 22.5% ± 11.0% of their weight forward on average, while linear hitters shifted 75.8% ± 20.7% of their weight forward on average. However, as shown in Figure 14b, when classified by the players own self-identification, rotational hitters shifted 45.0% ± 37.0% of their weight forward on average, while linear hitters shifted 57.8% ± 24.8% of their weight forward on average. Even before doing a t-test, one can immediately notice that there is no longer a large difference between percent weight shift forward in a rotational model and a linear model. And furthermore, that the error bars are much larger for the models that were self-identified, meaning that the weight shifts put into these categories were more different and the data was more spread out. This can be confirmed by a t-test, which indicates that the average percent weight shift forward in the rotational self-identified model is not statistically significantly different than the weight shift forward of the linear self-identified model. This means that when having players self-identify their swings, the percent weight shift forward no longer becomes a distinguishable attribute of the swing since no players can not accurately identify which model their swing belongs to with statistically significance of even 80% confidence. This confirms quantitatively the speculation from the qualitative interviews that players are statistically not good at identifying their own hitting model based on their weight shift forward.

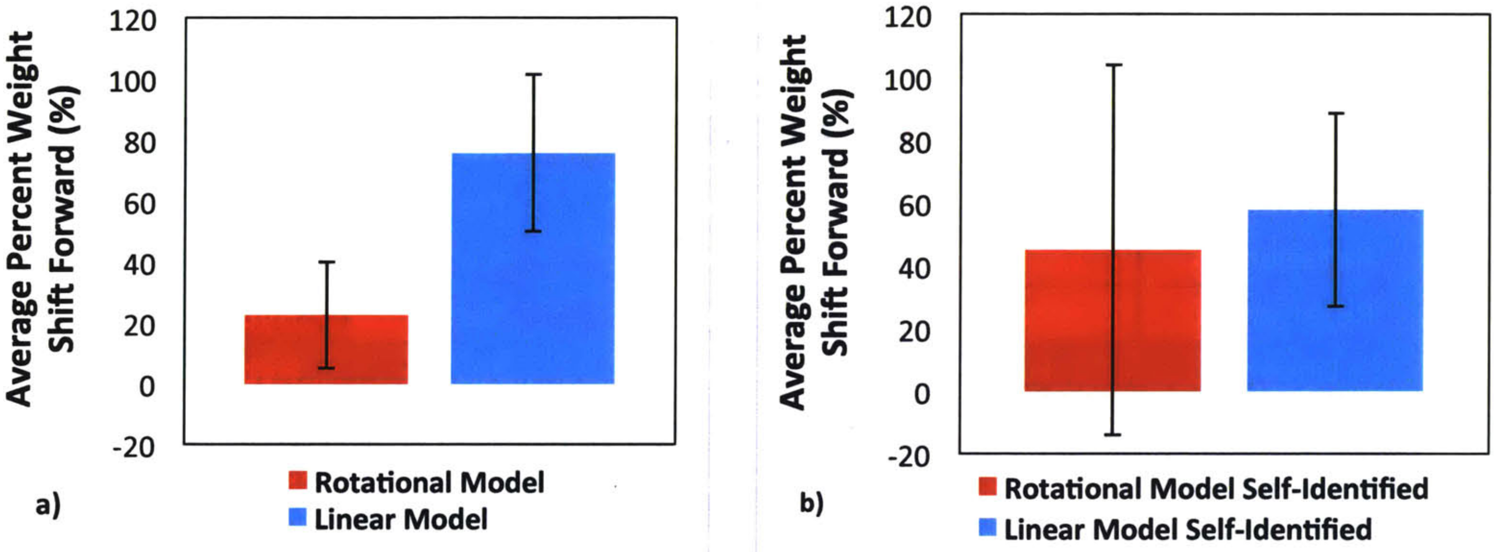

Figure 14: a) This figure depicts the percent of their weight the hitter shifts forward with, depending on which model they use, according to the definition that the rotational model is comprised of hitters who shift less than 50% of their weight forward, while the linear model is comprised of hitters who shift more than 50% of their weight forward. The error bars in these graphs are the statistical uncertainties. Here, rotational hitters shift 22.5% ± 11.0% of their weight forward, while linear hitters shift 75.8% ± 20.7% of their weight forward. The percent weight shift forward between rotational and linear models is statistically different with a 95% confidence; b) This depicts how much weight a hitter shifts forward, with the models classified only by how a hitter classifies herself. In this case, rotational models shift 45.0% ± 37.0% of their weight forward. The percent weight shift forward between self-identified rotational and linear models is not statistically different with a 95% confidence.

In terms of the bigger picture in the softball realm, if a player's weight shift forward matters in terms of producing large ball velocity, then this finding would necessitate a means for hitters to be able to get feedback on the weight shift. Since players are unable to identify their own weight shift, there would need to be a new sports invention that would allow real-time feedback for hitters on their weight shift forward. Although this invention could take many forms, one idea could be to have a mat with lightweight force sensors inside, and, much like a scale, have display where the player could see their percent weight shift forward by looking down after a swing. That way, after each swing, a player would know exactly what percentage of their weight they are shifting forward and how to improve this weight shift in order to maximize ball velocity. However, an invention like this is only needed if weight shift forward is in fact proven to correlate with ball velocity.

4.2 Linear and Rotational Bat and Ball Velocity

The next step in this analysis is to determine if the weight shift forward of these models is an important factor in producing large bat velocity, and subsequently, large ball velocity. As stated before, if it is, then this will change the way the softball community trains since there will need to be better implementations of feedback methods for weight shift forward. If not then coaches and players alike should spend less time working on weight shift, and more time on other components that will affect ball velocity.

As Figure 15 depicts, it was calculated that the average bat speed of a rotational swing was 20.4 ± 0.5 m/s, while the average bat speed of a linear swing was 21.9 ± 1.7 m/s. A t-test revealed that these velocities are statistically significantly different, with 90% confidence. Therefore, a linear model swing, with 90% confidence will statistically have a larger bat velocity than a rotational model swing.

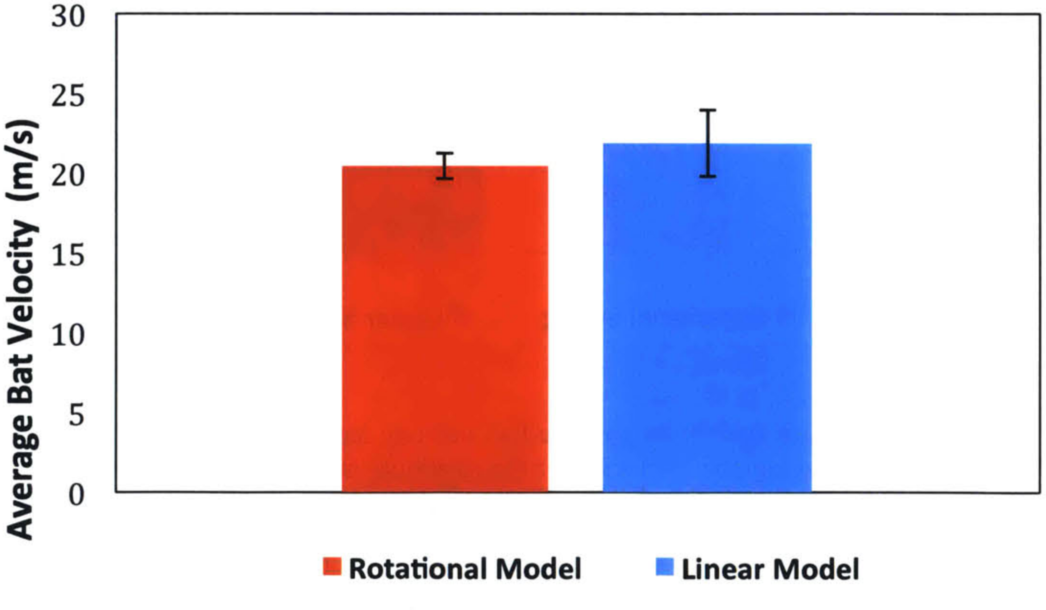

Figure 15: This figure shows the average bat velocity of the rotational model, comprised of the four rotational hitters, and the average bat velocity of the linear model, comprised of the five linear hitters. The average bat velocity for the rotational hitters was 20.4 ± 0.5 m/s, while the average bat speed of a linear swing was 21.9 ± 1.7 m/s. A t-test reveals that these bat velocities are statistically significantly different with a 90% confidence.

Given this data, it would be reasonable to assume then that the linear model also produced greater ball velocity than the rotational model since now the linear model has both larger weight shift and a larger bat velocity than the rotational model. However, as shown in Figure 16, this is not the case. In fact, the two ball velocities are statistically indistinguishable, with only different uncertainties. It was found that the ball velocity for the rotational model was 22.0 m/s ± 0.7 m/s and the ball velocity for the linear model was 22.0 m/s ± 1.9 m/s. These two velocities are not statistically significant with a 95% confidence, so therefore we can conclude that the rotational model nor the linear model is a better model to produce greater ball velocity. Since in this experiment, the models were distinguished by weight shift, we can go one step further to claim that weight shift forward does not affect ball velocity. This can be further shown by Figure 17, which depicts how ball velocity and weight shift are not correlated. Again, this reconfirms the conclusion that ball velocity does not depend on how much a hitter shifts their weight forward.

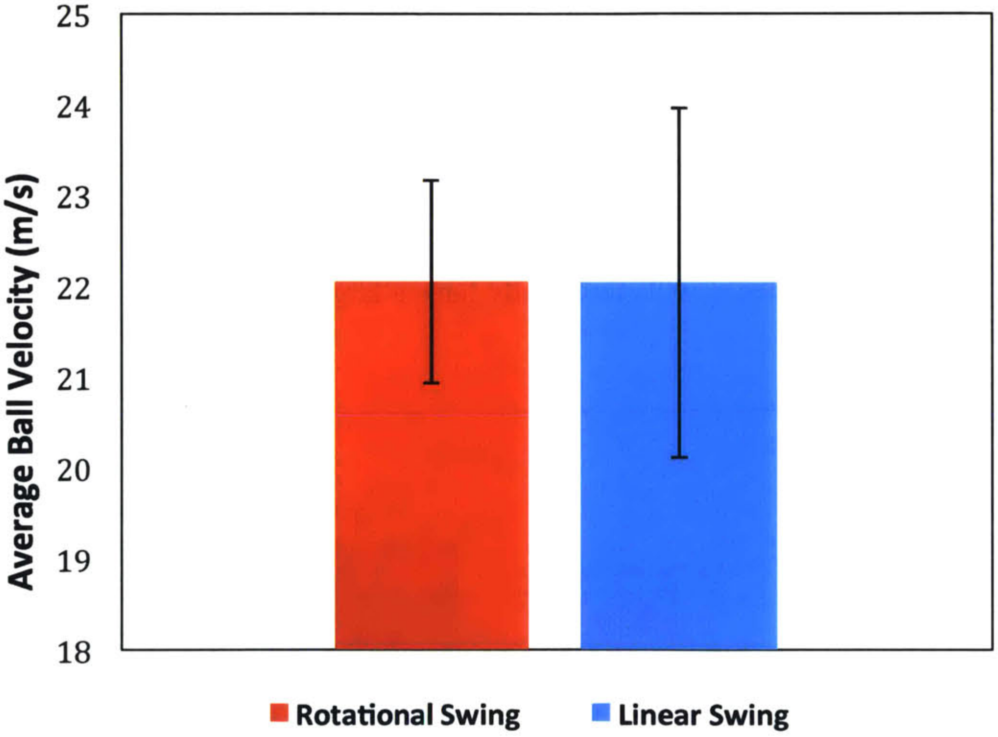

Figure 16: This figure depicts the average ball velocity for the rotational model and the linear model. The average ball velocity for the rotational model was 22.0 m/s ± 0.7 m/s, while the average ball velocity for the linear model was 22.0 m/s ± 1.9 m/s. These velocities were not statistically significantly different with a 95% confidence.

Although ball velocity has been proven to correlate with bat velocity in other studies, this data did not find a high correlation between the two, as shown further by Figure 18 [7]. The reasons for this range from simply not having enough data points to having too many data points with too similar bat velocities. Even though the bat velocities have a statistically significant difference, the bat velocity of the linear model was only 7.4% higher than the bat velocity of the rotational model. Therefore, to see more of a correlation between bat velocities and ball velocities, there may need to be a wider spread of data on bat velocities. In addition to this, it is important to recognize that although large bat velocity is a key component to producing a large ball velocity, this is by far not the only component in this complex system. Other factors that could affect the ball velocity are the angle at which the bat hits the ball, the amount of energy that is lost due to spin on the ball, what part of the bat the ball is hit on, and many more. Even with the same bat velocity, the probability of two curved surfaces (the bat and the ball) colliding in the exact same manner is extremely small. Therefore, although bat velocity does have an immediate effect on ball velocity in the grand scheme, once the bat velocities are close enough together in magnitude, other factors, such as those previously listed, can take over to effect ball velocity more.

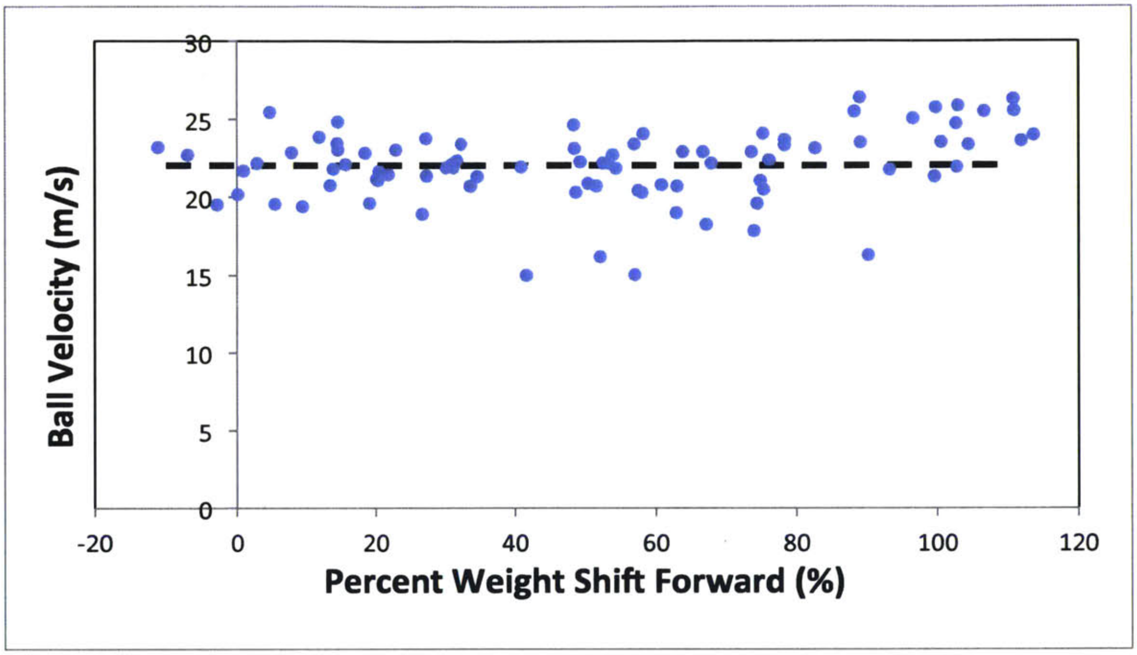

Figure 17: This graph shows that there is no correlation between the percent weight shift forward (%) of a hitter and the ball velocity (m/s) for a given swing. The standard error is 2.3 m/s, which indicates that this graph is relatively precise in its finding. The dotted line is the mean line, which shows that although there is no correlation in the data, the data is close to the line, which indicates the data is precise.

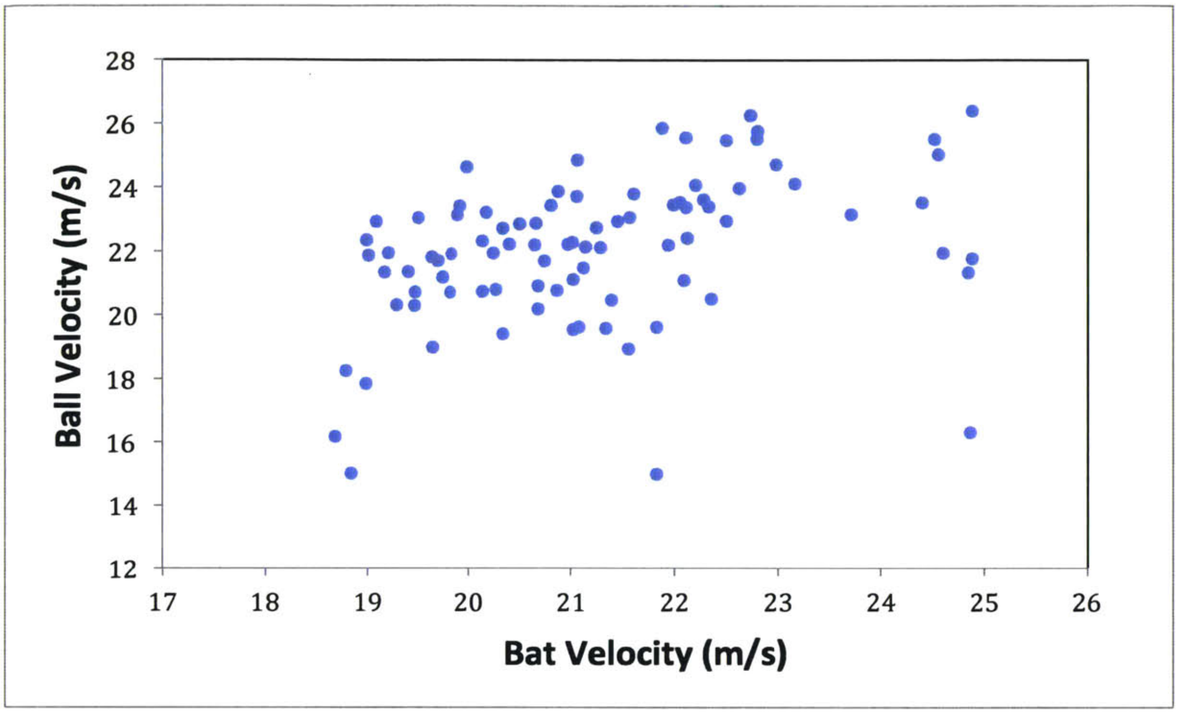

Figure 18: This plot shows the bat velocity (m/s) vs the ball velocity (m/s) for each hit recorded in the experiment. The linear correlation is relatively low, which indicates a nonlinear relationship. This may be due to the fact that bat velocities in this experiment were too similar to achieve a full relationship of bat and ball velocity correlation, or that there were simply not enough data points.

4.3 Additional Observation: Effect of Ball Presence on Hitting Mechanics

A final interesting observation that was noted during this experiment was the effect the presence of a ball had on players' hitting mechanics, specifically their weight shift forward and their bat velocity. As noted before, this experiment was composed of nine players, who each took 10 swings with a ball on a tee, and 10 swings without a ball on a tee. As shown in Figure 19, the weight shift for the rotational model increased to 41.6 ± 7.7% when there was no ball, and the weight shift for the linear model decreased to 67.9 ± 13.9 %. The difference between the rotational weight shift forward with and without a ball is statistically different with a 95% confidence. This means that the percent weight shift forward for a rotational swing when there is no ball is greater than when there is a ball present. Similarly, the difference between the linear weight shift forward with and without a ball is statistically different with an 80% confidence. Again this means that the percent weight shift for a linear swing when there is no ball is less than when there is a ball present. Simply put, the weight shift increases for the rotational model, but decreases for the linear model. And to further this point, when taking a t-test between the rotational model and linear model weight shifts for no ball present, it is revealed that these two data sets are not statistically significantly different, which means when there is no ball present, there is no longer a distinguishable difference in weight shift between a rotational and linear model.

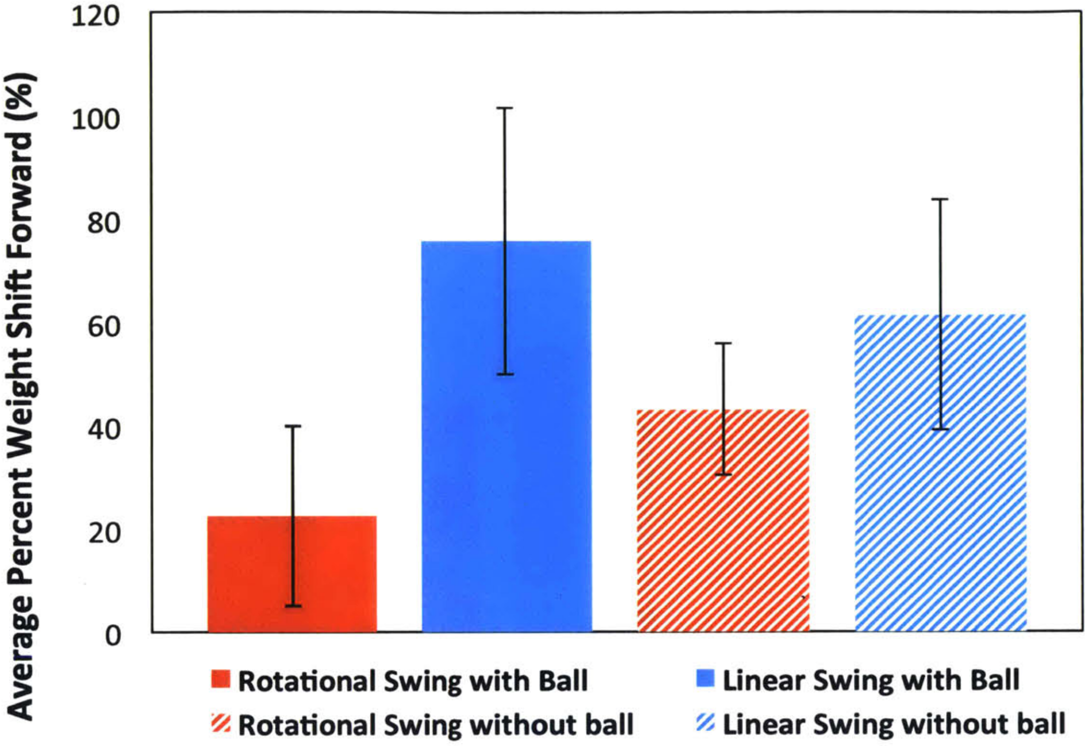

Figure 19: This figure shows the average percent weight shift forward for the rotational swing with and without a ball, and the average percent weight shift forward for the linear swing with and without a ball. The weight shift for the rotational model increased to 41.6 ± 7.7% when there was no ball present, and the weight shift for the linear model decreased to 67.9 ± 13.9 % when there was no ball present. The difference between the rotational weight shift forward with and without a ball is statistically different with a 95%, while the difference between the linear weight shift forward with and without a ball is statistically different with an 80% confidence.

There could be many reasons for this observation. One potential theory to explain this phenomenon is by viewing the presence of the ball as a kind of pinpoint, or anchor, for players when they swing. For the rotational model, the ball gave the hitters something to rotate around, a defined axis to swing about, while for the linear hitters, it gave them something to shift their weight towards. Without the ball, or this anchor, both models become less pure and more of a hybrid of the two swings. However, this is only one potential reason to explain this observation, and there could be many other factors that cause this to happen. Because this was not the main objective of the paper, no clear conclusion can be made on why this occurs and more tests have to be done to confirm and explain this observation.

Lastly, as shown in Figure 20, the bat velocity for the rotational model decreased to 19.0 ± 1.5 m/s with no ball, and for the linear model, it decreased to 20.5 ± 2.2 m/s. For the rotational model, there is a statistically significant difference in bat velocity between swinging with a ball and no ball, with 85% confidence. For the linear model, there is a statistically significant difference in bat velocity between swinging with a ball and no ball, with 90% confidence. The decrease in bat velocity when there is no ball present may be due to the fact that there is no longer a specific point for the player to accelerate to and thus do not swing as fast. But again, this is just one theory for this observation and there are many other reasons that this could be the case.

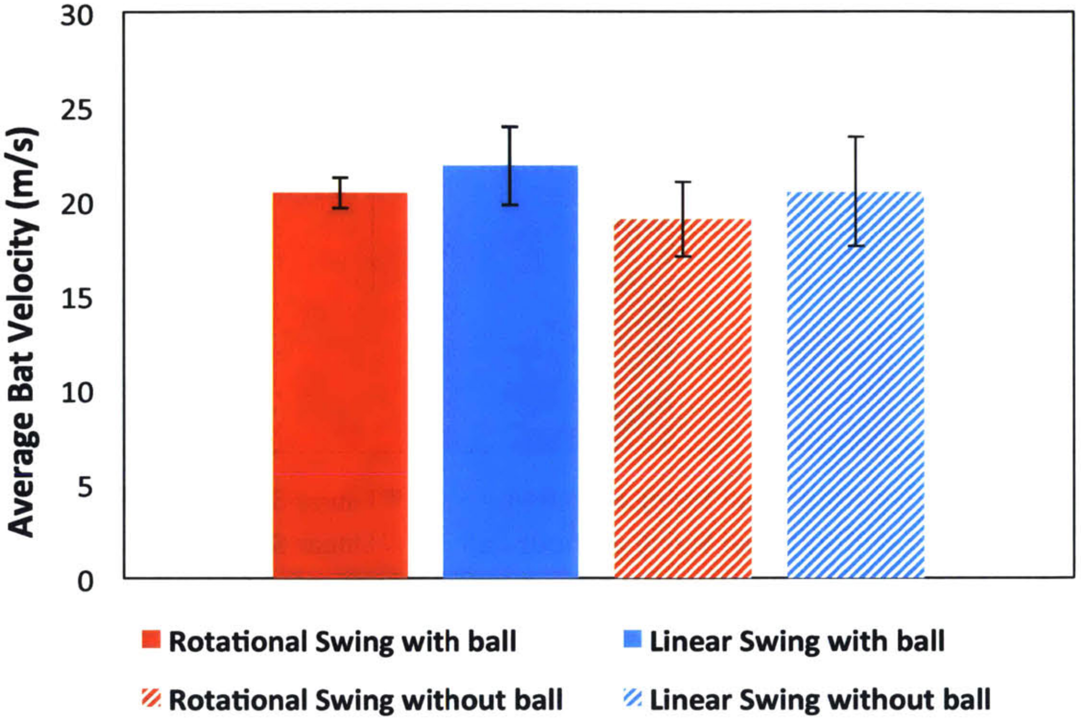

Figure 20: This figure depicts average bat velocity for the rotational swing with and without a ball, and the average bat velocity for the linear swing with and without a ball. The average bat velocity for the rotational model decreased to 19.0 ± 1.5 m/s when there was no ball present, and the average bat velocity for the linear model decreased to 20.5 ± 2.2 m/s. The difference between the rotational average bat velocity with and without a ball is statistically different with a 85%, while the difference between the linear average bat velocity with and without a ball is statistically different with an 90% confidence.

5. Conclusions and Future Work

Although these findings were based on small sample size of nine players, some clear conclusions were obtained through these experiments. The first was that there are in fact, two clear, distinguishable hitting models when defined by the percent of a player's weight shift forward. It was found that rotational hitters shift 22.5% ± 11.0% of their weight forward on average, while linear hitters shift 75.8% ± 20.7% of their weight forward on average, and that these two data sets are statistically significantly different, with 95% confidence. This means that the weight shift forward of these models is a unique and defining characteristic of the model. The second conclusion that was discovered was that when asked to self-identify their hitting model, players struggled to correctly identify themselves. It was noted that perhaps the model that a player was taught before adolescence is the model that most influences them today, whether they are consciously aware of that or not. When the hitting models were divided upon the lines of where each player identified themselves, rotational hitters now shifted 45.0% ± 37.0% of their weight forward on average, while linear hitters shifted 57.8% ± 24.8% of their weight forward on average. The average percent weight shift forward in the rotational self-identified model was not statistically significantly different than the weight shift forward of the linear self-identified model. This means that when having players self-identify their swings, the percent weight shift forward no longer becomes a distinguishable attribute of the swing since no players can not accurately identify which model their swing belongs to with statistically significance of even 80% confidence.

It is important to note that although only weight shift forward during the swing was thoroughly analyzed in this paper, the weight shift backward before the swing is another component that could be further investigated in future work since this weight shift varied greatly between each batter and could yield deeper insight into hitting mechanics.

From here, the bat velocities of each hitting model were analyzed, and it was revealed that the average bat speed of a rotational swing was 20.4 ± 0.5 m/s, while the average bat speed of a linear swing was 21.9 ± 1.7 m/s. A t-test revealed that these velocities are statistically significantly different, with 90% confidence. Given this data, it would be reasonable to assume then that the linear model also produced greater ball velocity than the rotational model since now the linear model has both larger weight shift and a larger bat velocity than the rotational model. However, this was not the case. In fact, the two ball velocities are identical, with only different uncertainties. It was found that the ball velocity for the rotational model was 22.0 m/s ± 0.7 m/s and the ball velocity for the linear model was 22.0 m/s ± 1.9 m/s. These two velocities are not statistically significant with a 95% confidence, so therefore we can conclude that the rotational model nor the linear model is a better model to produce greater ball velocity. Since in this experiment, the models were distinguished by weight shift, we can go one step further to claim that weight shift forward does not affect ball velocity.

Although ball velocity has been proven to correlate with bat velocity in other studies[2], this data did not find a high correlation between the two. There could be many reasons for this, from simply not having enough data points to having too many data points with too similar bat velocities. Although most players would never intentionally swing slower, with the exception of slap hitters, if this experiment had tested players with a greater range of skill, as the previous study had, there would be a greater ranger of bat velocities, which would produce a greater range of ball velocities to study this correlation. However, since this experiment deliberately chose collegiate softball players with a similar skillset, there was not as diverse a set of bat velocities as in other studies [7]. Although this may seem like a limitation to this study, this choice actually adds to the field of research on hitting mechanics since the lack of correlation between ball velocity and bat velocity observed in this study may point to the fact that once players reach a consistently large enough bat velocity, the ball velocity begins to be effected by other subtle factors, such as potentially the angle of the bat or the location the ball is hit at.

Even though the bat velocities have a statistically significant difference, the bat velocity of the linear model was only 7.4% higher than the bat velocity of the rotational model. Therefore, to see more of a correlation between bat velocities and ball velocities, there may need to be a wider spread of data on bat velocities, as there was in the other study which had participants from all skill levels [7]. To reiterate, it is important to recognize that although large bat velocity is a key component to producing a large ball velocity, this is by far not the only component in this complex system. Other factors that could affect the ball velocity are the angle at which the bat hits the ball, the amount of energy that is lost due to spin on the ball, what part of the bat the ball is hit on, and many more.

Finally, the effect having a ball present during a swing on a player's hitting mechanics was observed. For the rotational model, the weight shift increased to 41.6 ± 7.7% when there was no ball, and the weight shift for the linear model decreased to 67.9 ± 13.9 %. The difference between the rotational weight shift forward with and without a ball is statistically different with a 95% confidence. This means that the percent weight shift forward for a rotational swing when there is no ball is greater than when there is a ball present. Similarly, the difference between the linear weight shift forward with and without a ball is statistically different with an 80% confidence. Again this means that the percent weight shift for a linear swing when there is no ball is less than when there is a ball present. Simply put, the weight shift increases for the rotational model, but decreases for the linear model. A hypothesis for why this might be the case is that the presence of the ball gave the hitter a pinpoint to focus on. For the rotational model, the ball gave the hitters something to rotate around, a defined axis to swing about, while for the linear hitters, it gave them something to shift their weight towards. Without the ball, or this anchor, both models become less pure and more of a hybrid of the two swings.

Lastly, the bat velocity for the rotational model decreased to 19.0 ± 1.5 m/s with no ball, and for the linear model, it decreased to 20.5 ± 2.2 m/s. For the rotational model, there is a statistically significant difference in bat velocity between swinging with a ball and no ball, with 85% confidence. For the linear model, there is a statistically significant difference in bat velocity between swinging with a ball and no ball, with 90% confidence. Again, the decrease in bat velocity when there is no ball present may be due to the fact that there is no longer a specific point for the player to accelerate to and thus do not swing as fast.

In terms of softball, this paper has pointed at some critical components to reconsider when training and teaching hitting mechanics. The first is that it does not matter whether or not a hitter shifts their weight forward or not since the same ball velocity can be reached regardless of weight shift forward. Therefore, the softball community should stop arguing and taking up time discussing over whether the rotational or linear model is better based solely on weight shift forward. Finally, to get the most out of drills and practice swings with the greatest bat velocity, this research indicates that players should always take swings with a ball present. This gives the player an anchor to swing to, and will help keep their swing quick and compact.

In terms of future work, there is still a lot of ground to cover in understanding which hitting mechanic components produce the greatest ball velocity. In addition to collecting more data to expand this research of shifting weight during a swing, other studies may advance this research by comparing the bat angle of linear and rotational hitting upon contact with the ball and examining the effects of bat angle on ball velocity. Another interesting component to study would be the ball spin and how this affects the ball velocity. Additionally, it could be tested if one model produces greater ball velocity for different pitch locations since this study held the pitch location as an experimental constant. Finally, this study was purposefully performed on a tee with a stationary ball to eliminate additionally uncontrollable variables of ball velocity and ball spin coming into the hitter, as well as keeping the ball position a controlled variable. This was a deliberate choice in order to highlight solely the hitting mechanics which this paper was analyzing, but it is important to note that although this aided with data analysis, softball is not played off of a tee, and hopefully further studies will take into account the effect of the ball being pitched into a batter and observe how elements, such as timing of the swinging, effect the ball velocity. In the end, however, what this study did show was that both hitting models produce approximately the same average ball velocity. Although this is only one experiment, this is an important step forward since proponents of the linear model have been claiming it to be better for years, while likewise proponents of the rotational model have been claiming the same. This study clearly shows that there is no hitting model that produces a greater ball velocity, and therefore softball players should be encouraged to use the model that feels most comfortable to them, and coaches should focus on other components of the swing other than weight shift since this does not affect the ball velocity.

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