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The Effects Of Various Warm-Up Devices on Bat Velocity and Trajectory in Collegiate Baseball Players

Jordan L. Cola
jordan.cola@student.shu.edu

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THE EFFECTS OF VARIOUS WARM-UP DEVICES ON BAT
VELOCITY AND TRAJECTORY IN COLLEGIATE BASEBALL
PLAYERS

BY

Jordan L. Cola

Submitted in partial fulfillment of the requirements for the degree
of Doctor of Philosophy in Health Sciences
Seton Hall University
2016

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APPROVAL FOR SUCCESSFUL DEFENSE
School of Health and Medical Sciences

Doctoral Candidate Jordan L. Cola has successfully defended and made the required modifications to the text of the doctoral dissertation for the Ph.D. during this Fall Semester 2015.

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(Please sign and date beside your name)

Chair:
Genevieve Pinto Zipp, PT, Ed.D

Genevieve Pinto Zipp PT, Ed.D

Committee Member:
Fortunato Battaglia, M.D., Ph.D

Fortunato Battaglia M.D., Ph.D

Committee Member:
Gavin Moir, Ph.D.

Gavin Moir Ph.D

The mentor and any other committee members who wish to review revisions will sign and date this document only when revisions are completed. Please return this form to the graduate office at graduate studies, where it will be placed in the candidates file and submit with your final dissertation.

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ABSTRACT

THE EFFECTS OF VARIOUS WARM-UP DEVICES ON BAT VELOCITY AND TRAJECTORY IN COLLEGIATE BASEBALL PLAYERS

Jordan L. Cola

Seton Hall University, 2016

Dr. Genevieve Pinto-Zipp, Chair

Purpose: The purpose of this study was to examine the effects of various weighted warm-up devices on standard baseball bat velocity and trajectory in collegiate baseball players. **Methods:** Three, right-handed hitters (mean age= 19.3yrs \pm 1.5yrs; height= 1.74m \pm .13m; mass=81kg \pm 20.4kg; baseball experience=14.2 \pm 1.3) volunteered for this study. Maximal bat velocity was obtained by swinging the 30oz standard bat for the control condition. Participants were then instructed to perform a *general* and *specific* warm-up with each of the weighted bats (standard bat with 16oz donut ring (46oz total) and standard bat with 24oz power sleeve (54oz total)) on separate days. Following the warm-up procedures, participants were instructed to swing 3 times with the 30oz standard bat for maximal velocity while impacting the ball resting on the tee located belt-high and in the middle of home plate. **Results:** No significant differences were revealed by Shewart Chart

method for baseball bat velocity or trajectory. Also, it was observed that all participants swung the bat at its lowest point in its trajectory for all conditions. **Conclusion:** Based upon no changes in the dependent variables in the population tested, Division II collegiate athletes can choose any of the warm-up devices investigated because no deleterious effects were observed.

Keywords: evenly-distributed, bat velocity, bat trajectory

Chapter I

INTRODUCTION

Baseball is a game which requires a mastery of many skills. Specifically, coordinated motor skills are needed to perform various tasks of the game such as fielding, throwing and hitting. Mastery of these skills is an essential prerequisite for the participants to possess to successfully progress to and compete at the collegiate level, increase personal performance and theoretically increase the instance of a game win. So how does one ensure that they are elevating themselves to this level of performance? Coaches design frequent practice sessions to address team needs as well as enhancing the skills of the individual player. During team practice sessions, a large percentage of time and effort is focused on training an effective baseball swing to improve hitting performance in game situations (Montoya, Brown, Coburn, & Zinder, 2009). There are many variations of the baseball swing; however, all variations of the swing share one extremely important aspect: bat velocity. Bat velocity is commonly referred to as bat speed or swing velocity, however, regardless of the nomenclature that one uses; generation of maximal bat velocity to translate to the thrown object after making contact with the baseball bat is an important component to successful hitting.

Successful hitting and the classification of being a 'good hitter' are synonymous with one another. According to college and professional baseball standards, a 'good' or successful hitter has a batting average above .300 (Escamilla et al., 2009); in other words the batted ball will land in the field of play as a recorded hit at least thirty percent of the total at bats attempted. The speed at which a ball leaves a bat, the hit speed, is a fundamental element in a successful hitting (Koenig, Mitchell, Hannigan, & Clutter, 2004). Batted ball velocity is dependent upon numerous factors, among which the velocity of the bat plays an integral role. In fact, holding all other factors constant, batted ball velocity is directly proportional to the velocity of the baseball bat contact point at impact (Koenig, Mitchell, Hannigan, & Clutter, 2004), as revealed by Kirkpatrick (1963), Brody (1986) and Hester & Koenig (1993).

Baseball bat velocity is influenced by several factors. Velocity of the bat is a factor in the ability of the hitter to properly position a bat both temporally and spatially during the swing after recognition of type and location of the pitch (Koenig, Mitchell, Hannigan, & Clutter, 2004). Bat control is the ability of the hitter to accelerate the bat towards the thrown object or decelerate the bat if the decision is made to not swing (Koenig, Mitchell, Hannigan, & Clutter, 2004). In terms of the integral of the acceleration throughout the swing, bat velocity represents the

measure of how well the hitter can locate the bat at the proper place at the appropriate time to make contact with the thrown object (Koenig, Mitchell, Hannigan, & Clutter, 2004), which clearly demonstrates that bat velocity is an extremely important component to successful hitting during a game situation.

Furthermore, the importance of bat velocity is directly related to the speed at which the baseball is thrown toward the hitter. Fastball velocities at the college level range from 87-95 miles per hour, with an overall average of 91 miles per hour (NCSA). At this velocity, the batter has .4 seconds to react to the thrown baseball (Weiskopf, 1975). With this finite window of time for the hitter to react to the thrown object, increased bat velocity produced by the hitter is essential to make contact with the incoming ball traveling at a high velocity. Once the hitter consciously makes the decision to initiate the swing towards the incoming pitch, the velocity of the bat becomes even more important. Maximum bat velocity meeting maximum ball velocity will produce maximal force against the baseball resulting in maximal velocity of the batted ball and an increase in the distance traveled by the hit ball following impact (Adair, 1990). Adair further exemplifies this notion with his finding of a positive relationship between bat velocity and the distance the ball travels after impact.

In an attempt to increase bat velocity and subsequently increase velocity and distance traveled by the batted ball, coaches and trainers suggest the use of various devices which can be added to the player's 30oz game bat during batting warm-ups. Based upon coaches input, baseball players from the Little League level to those playing in Major League Baseball traditionally swing weighted bats in the on-deck circle to warm-up prior to stepping in the batter's box to face live pitching. While the actual nature of the warm-up routine may differ from hitter to hitter, the warm-up devices remain relatively consistent. Today, amateur and professional baseball players commonly use a 16oz. donut ring or 24oz. Pow'r Wrap added to the player's game bat during warm-ups prior to stepping in the batters' box.

The underlying premise or idea behind swinging an overweight warm-up bat in the on-deck circle prior to swinging a standard 30oz bat is that since motor unit activity of skilled coordinated motor movements follow a definitive sequence, the additional motor units activated by the over-weighted warm-up device may continue to function when the extra load is removed, resulting in greater bat velocity when swinging the standard bat (DeRenne, Ho, Hetzler, & Chai, 1992), thus subsequently augmenting performance. If the bat velocity is increased while swinging a standard bat, the increased velocity will result in a greater exit velocity of the batted-ball, meaning the baseball would be

hit harder and farther. A batted ball with a higher velocity immediately after impact has a higher probability of becoming a recorded hit for the hitter rather than a recorded out for the opposing team, thus increasing the hitters performance (batting average, home runs, slugging percentage) (Szymanski et al., 2011) and theoretically increasing team's chance to successfully achieve a team win.

In contrast, it has been proposed that the dynamic wielding of an over-weighted device and the subsequent removal of the overload had no significant effect on post warm-up speed of movement, but only created a kinesthetic illusion of increased speed (DeRenne, Ho, Hetzler, & Chai, 1992). It is clear that previous studies of the effects of weighted warm-up situations on bat velocity have shown inconsistencies. Warm-ups using heavier bats have been shown to produce increased swing velocities (Reyes & Dolny, 2009), decreased swing velocities (Southard & Groomer, 2003; Montoya et al., 2009; DeRenne, Ho, Hetzler, & Chai, 1992), and unaltered swing velocities (Szymanski et al., 2011) as compared to standard baseball bats depending upon the study reviewed.

Given the diversity of commercially available devices that a hitter can choose from to alter the weight of the bat during warm-up swings, along with discrepancies in the literature as to which device or the amount and/or location of the added weight produces the greatest

post warm-up bat velocity, the question of ‘Which warm-up device elicits the greatest post warm-up bat velocity?’ remains unclear, as does the degree and/or location of the additional weight. Therefore, the focus of this study was to provide an evidence based perspective on the use of an evenly distributed overweight warm-up bat device to further extend the knowledge and understanding of the use of overweighted devices on post warm-up baseball bat velocity. The use of overweight bats encompasses all levels of play. With such a large population using these devices, more information is needed to obtain a greater comprehension of the complex biomechanical variables and strength and conditioning techniques utilized to maximize performance during a game situation for baseball hitters.

Statement of the Problem

Given the inconsistencies of the literature that has shown various effects on post warm-up bat velocity using various devices on the game time bat, it is not mutually accepted as to which device is more advantageous to the athlete prior to stepping into the batter’s box. Currently, there is a paucity of studies that focus on the effects of an evenly distributed warm-up device. In fact, only one study has mentioned the use of an evenly distributed device which was investigated only in an underweight condition. Although there is a great deal of data obtained by previous studies using an overweight device,

the question of the effects of an evenly distributed bat remains unanswered.

Purpose of the Study

The purpose of this study was to examine the effects of various weighted warm-up devices on standard baseball bat velocity and trajectory in collegiate baseball players.

Research Questions

What effect does weighted, distally located warm-up devices (16oz donut & 24oz Pow'r sleeve) and an evenly distributed (16oz & 24oz) weighted baseball bat have on post warm-up velocity when using a standard 30oz baseball bat?

What effect does weighted, distally located warm-up devices (16oz donut & 24oz Pow'r sleeve) and an evenly distributed (16oz & 24oz) weighted baseball bat have on post warm-up bat trajectory when using a standard 30oz baseball bat?

Hypotheses

Due to the inconsistencies in the literature while using an overweight warm-up device as previously discussed and the scarcity of evidence of the use of an evenly distributed bat used as a warm-up device, null hypotheses were developed. The following hypotheses were tested:

H₁: There will be no differences between distally located warm-up devices (16oz donut & 24oz Pow'r sleeve) and an evenly distributed (16oz & 24oz) device on post warm-up velocity with a standard 30oz baseball bat.

H₂: There will be no differences between distally located warm-up devices (16oz donut & 24oz Pow'r sleeve) and an evenly distributed (16oz & 24oz) device on post warm-up bat trajectory with a standard 30oz baseball bat.

Chapter II

REVIEW OF LITERATURE

Bat velocity is an integral part of successful hitting. Attempting to increase bat velocity prior to stepping into the batter's box is a practice commonly achieved by dynamically wielding an altered baseball bat, usually an overweight bat, to encourage an increase in bat velocity while using a lighter bat typically used during a game situation. However, the device added to the players bat varies greatly from athlete to athlete, as well as the manner in which they warm-up. Various types of weighted devices are commercially available to the athlete; however, it is not mutually accepted in the literature as to which device is more advantageous to maximize bat velocity prior to stepping into the batter's box.

Various devices have been investigated in various populations and protocols with inconsistencies of their effects on post warm-up bat velocity. With these inconsistencies, the need to expand the knowledge of various devices and how they affect bat velocity is crucial to further the understanding of the effects and to be able to select an appropriate warm-up device to maximize bat velocity. Furthermore, to introduce a novel warm-up device into the literature and understand its effects of bat velocity while possibly providing an alternative to the commercially available devices.

This study was not the first attempt to analyze collegiate baseball players post warm-up bat velocity while swinging a standard 30 ounce bat immediately following a warm-up with an over weighted device. However, to the best of the author's knowledge, it is the first comprehensive attempt to analyze the effects of an evenly distributed, overweight warm-up device on a standard baseball bat velocity.

The first section (2.1.1- 2.1.3) of this literature review will summarize prior related research studies of the baseball swing while focusing on the chronological review of kinematic studies (2.1.1), electromyography (EMG) (2.1.2), and kinetics (2.1.3). It should be noted that the first section of kinematics is slightly more relevant than EMG and kinetics. However, it is essential to integrate kinetic and EMG studies into the review to allow for a more complete understanding of the skills that are necessary to possess to successfully complete to task of hitting a baseball. Next, section 2.1.4 will focus on joint kinetics and in the intricacies behind the kinetic chain theory and why this theory may be lacking in explaining the entirety of the movement related to other explosive ballistic movements. Following the joint kinetics section, a brief summary of swing trajectory (2.2) will be explored to give the reader a better understanding of the spatial and temporal location of the bat when attempting to make contact with the baseball.

Next, the effects of various weight bats on bat velocity will be examined (2.3). Hitters from all levels utilize these devices yet there are such discrepancies in the literature as to which one serves as the most advantageous device when swinging a standard 30 ounce baseball bat during a game situation. The reader should be familiar with literature concerning the use of these devices and the implications on bat velocity post-warm with a weighted bat. Also, a brief section (2.4) to explain how the motor system changes accordingly to a weighted device when dynamically wielding a heavier bat; then to a standard bat along with the kinesthetic effects induced by a weighted tool on movement correction. Following the kinesthetic aftereffect section, the location of the moment of inertia (2.5) will be examined to understand the effects of bat mass and moment of inertia interrelates to the baseball swing. Finally, sport specificity (2.6) will be reviewed to allow the reader to understand the different types of warm-up (training) and how that will transfer to the actual hitting (2.6.1) during a game.

The field of biomechanics can be broken down into subdivisions of: kinematics, kinetics and electromyography (EMG). As Hamill and Knutzen (2006) define, kinematics is concerned with motion characteristics and examines motion from a spatial and temporal perspective without reference to the forces causing the motion. A kinematic analysis involves the description of movement to determine

how fast an object is moving, how high it goes, or how far it travels (Hamill & Knutzen, 2006). Thus, position, velocity and acceleration are the components of interest in a kinematic analysis (Hamill & Knutzen, 2006).

Kinetics is the area of study that examines the forces acting on a system, such as the human body, or any other object (Hamill & Knutzen, 2006). A kinetic movement analysis attempts to define the forces that cause the movement. Using a full kinematic description, anthropometric measurements, and external forces, joint reaction forces and muscle moments can be estimated (Fortenbaugh, 2011).

To visually observe the activity at the muscle level, one must investigate EMG data. This is the sum of the energy from all muscle action potentials detected by the recording electrode during a muscular contraction (Criswell, 2010). The previous components have been investigated to various extents while performing the baseball swing. The subsequent subsections will examine the outcomes in these particular areas.

2.1.1 Chronological Review of Kinematic Studies

Prior to the year 1983 (Ginsberg, & Maxwell, 1986), when three-dimensional optical motion capture systems were beginning to revolutionize the manner in which human movement were collected

and analyzed, biomechanical studies were required to use two-dimensional cinematographic film to obtain information on how the human body moves. Despite the inherent limitations of using such primitive technology, two-dimensional collection and analysis paved the way for future researchers by scientifically establishing the rudimentary movements of the baseball swing. Race (1961) with the assistance of a 16mm camera, along with the swings of seventeen professional baseball players, introduced one of the original qualitative and quantitative breakdowns of the baseball swing. His work was the first to bring together concepts of judgment of time, kinetic linking, angular measurement and balance. Also, this was the first study to investigate the cinematographic and mechanical analysis of the baseball swing by quantifying professional adult hitters' linear and angular displacements and velocities of the baseball bat, along with specific upper-extremity and trunk parameters. It was reported that hitters displayed clear evidence of linear hip velocity ($2.42 \text{ m}\cdot\text{s}^{-1}$ average over a 90° arc) along with definitive wrist action ($4.89 \text{ m}\cdot\text{s}^{-1}$ average over a 90° arc) (Race, 1961).

As cited in the work of Fortenbaugh (2011), Swimley (1964) has established that the swing of an individual who typically hits for power, which is defined as a batter that normally 'pulls' the baseball after contact to the same side of the field relative to the side of the batter's

box that they are standing (right field for a left-handed hitter), had a larger pelvis angular velocity than a hitter who attempts to hit the baseball to the entire field (left, center and right). Breen (1967) was the first to answer the question of "What makes a good hitter?" After studying thousands of feet of film and hundreds of professional hitters, it was concluded that with the differences in outward appearance (anthropometrics), elite hitters such as Ernie Banks, Ted Williams, Henry 'Hank' Aaron, Willie Mays, and Mickey Mantle, all with varying hitting styles have five specific points in common. These commonalities are as follows: the center of gravity (CoG) of the body follows a fairly level plane throughout the swing, the ability to adjust the head from pitch to pitch to get the best and longest possible look at the flight of the ball, immediate straightening of the forearm at the beginning of the swing to increase bat velocity, consistent stride length for all pitches and an upper body position that is in the same direction as the flight of the baseball which positions the hitters weight on the front foot following ball contact (Breen, 1967).

In an attempt to discriminate between skilled and unskilled hitters, Hirano (1986) conducted a study where right handed hitters were instructed to hit a pitched baseball to the same field (left field) while a 16mm camera sampling at a rate of 200Hz collected data from ten meters above the hitter to capture movements in the horizontal

plane. Linear velocity of the CoG of the bat for the skilled hitters was kept constant after landing of the striding foot (ST) and it was rapidly increased .1 seconds prior to the ball contact (C). For the unskilled hitters, linear velocity was progressively increased after ST. For the skilled hitters the mean maximum value of linear velocity obtained at C was 22.6m/sec; while, the unskilled hitters linear velocity which occurred at an average of .01seconds prior to C, was19.9m/sec (Hirano, 1986). Also, skilled hitters were shown to have a greater value of mean maximum kinetic energy (274.0J) than their unskilled counterparts (227.5J). The difference in these values was due to the difference in the maximum values of the linear kinetic energy; in other words, the skilled hitters had greater linear bat velocity than the unskilled immediately prior to C (Hirano, 1986). The decrease in linear bat velocity, which was observed in the unskilled hitter, may be attributed to a misuse of the hip rotation or inaccurate timing for the onset of the swing; however, the unskilled hitters showed greater values of total kinetic energy by -.04 seconds prior to C (Hirano, 1986).

It is considered that one of the characteristics possessed by skilled hitters is the production and rapid increase of bat velocity just prior to contact while achieving greater velocity at contact (Hirano, 1986). However, the unskilled hitters' linear velocity progressively increased after stride and the maximum value of linear velocity was

obtained at about .04 seconds prior to contact (Hirano, 1986). Also, considering that changes in the mechanical energy of the bat are equal to the amount of the work done, the unskilled hitter seems to work inefficiently for the energy flow from body segments to the bat during the swing (Hirano, 1986), which is dictated by the diminished value of kinetic energy, as a result of decreased linear velocity of the bat possessed by the unskilled hitters.

Movements in a successfully executed swing proceed in a sequential fashion with the hips, shoulder, arms, and finally the wrists and the bat being driven forcefully around to front (Hay, 1978). Hirano (1986) observed the relationship, from the angles of the hip and bat during the swing, that the unskilled hitter showed a greater displacement of the angle of the hip, along with an earlier increase in hip angle with respect to the bat than their skilled counterparts. Although it is considered that the greater the displacement in the hip angle, the more the amount of the work the hitter produces, the maximum angular velocity of the hip angle for the unskilled resulted in the lower value of angular hip velocity (Hirano, 1986). This lower value may be explained by the earlier increase in hip angle with respect to the angle of the bat. Furthermore, the pattern of displacement in angle of the left forearm (arm facing the pitcher for a right handed hitter) for the unskilled hitter showed wrist uncocking earlier than the skilled hitter

which is not preferable for the attainment of maximum segmental angular velocity (Hirano, 1986). This is because the unskilled hitter tends to increase the moment of inertia (MOI) of the arms, thus making it more difficult for the hitters to maximize velocity at the more distal segments of the wrist and hand (Hirano, 1986). Lower maximum pelvis angular velocity and premature extension of the wrists and elbows in the unskilled hitters further explains the decreased efficiency and differentiates the skilled hitters from the unskilled hitters during the swing.

McIntyre & Pfautsch (1982) also investigated the mechanics of hitting a baseball to the same and opposite fields. Their study investigated twenty former and current collegiate baseball players with the only inclusion criteria being they had to have been right-handed hitters. Each subject was then evaluated by the coach and rated as an 'ineffective' or 'effective' hitter to the opposite field. Identical to Hirano (1986), the subjects were filmed from above to capture the movement of the swing in the horizontal plane. Using the filmed data to obtain the x- and y- coordinates of the tip of the bat, handle of the bat, distal end of the third metacarpal of the left hand, left wrist joint, left elbow joint, left shoulder joint and the ball, linear displacements from an origin at the rear corner of home plate were calculated, as was the angular orientations of the examined segments and joints (McIntyre &

Pfautsch, 1982). Results revealed no significant interactions between the subject groups and the two types of field hits for all of the examined dependent variables. Also, an examination of the main effects exposed no significant differences between the subject groups. However, significant differences were found between the two fields hit conditions. Same-field hits had significantly more movement time from initiation to ball contact, significantly more angular displacement of the bat, lead hand, and lead forearm at the instant prior to ball contact, and significantly less maximum angular velocity of the bat, lead hand, and lead upper arm (Fortenbaugh, 2011; McIntyre & Pfautsch, 1982).

Furthermore, much like Hirano (1986) established, decreases in linear bat velocity prior to contact between the skilled and unskilled have been observed by McIntyre & Pfautsch (1982). With emphasis on the significantly greater maximum angular velocity of the bat, left hand arm in the opposite fielding hitting when compared to same field hitting, time for initiation of movements to contact with the ball for the same field condition must have increased to a proportional greater extent than the angular displacements of the segments as compared to the corresponding temporal/angular displacement increases for the opposite field condition (McIntyre & Pfautsch, 1982). It can be anticipated that the linear speed of the tip of the bat would decrease with corresponding decreases in angular velocity. With all of the

significant differences reported, the researchers concluded that the hitters adjust the amount of extension at the left elbow joint and the angle of the left wrist joint so that the bat obtains an appropriate orientation at the instant of ball contact (McIntyre & Pfautsch, 1982).

To further explain hitting to the same and opposite fields, Gelinas and Hoshizaki (1988) analyzed a 35 year old, 13 year Major League professional baseball player rated as an efficient opposite-field hitter by his coaches. Exactly like Hirano (1986) and McIntyre & Pfautsch (1982), a high speed camera sampling at 200Hz was utilized to film the movement from 4.62 meters above the hitter to capture movements in the horizontal plane while a pitching machine 'pitched' baseballs toward the hitter at a mean velocity of 33.5 m/s. Results presented, which are similar and support McIntyre & Pfautsch (1982), were calculated in the horizontal plane, with absolute values being relative to a straight line joining the middle of the pitching rubber with the middle of home plate. Mean angles (measured at contact) were compared. Using this method, it was established that opposite field (OF) hits were characterized by significantly smaller bat angular displacements at contact (Gelinas & Hoshizaki, 1988). The mean angle for the bat, at contact with the ball, were 73.1° for the OF hits, as compared to 103.3° for the same-field (SF) hits. Angular displacements about the left bat-forearm joint during the execution of both types of

field-hits revealed a significantly smaller angle for OF hits (139.7°) than for SF hits (157.3°) (Gelinias & Hoshizaki, 1988). Also, the hitter performed the OF hits with significantly less shoulder (upper trunk) (OF: 51.2° , SF 62.2°) and hip segment (pelvis) rotation (OF: 53.3° , SF: 67.5°) than SF hits (Gelinias & Hoshizaki, 1988). No significant differences were found between the displacement patterns of both types of field-hits about the left elbow and shoulder joints. A slight limitation to this study is that the pitching machine was utilized resulting the absence of visual cues which are normally presented to the hitter.

Visual cues are of the utmost importance to the hitter, as well as timing and eye-hand coordination. The main job of the pitcher is to attempt to throw the baseball past the hitter, effectively 'taking the bat out of the hitters' hands' by making it increasingly difficult for the hitter to make contact. This is done by randomly changing the velocity and location of the pitch to increase the difficulty for the hitter to successfully make contact. Matsuo, Kasai, & Asami (1993) conducted research on the changes and contributions required to improve coincidence anticipation timing performance in the baseball hitting task. Ten male subjects participated in the study, all with more than nine years baseball experience. Five of the nine participants are classified as 'top' players (active) while the remaining four were classified as 'good players' (inactive).

Participants were instructed to swing a bat so that it coincided with an apparent movement target at an impact point. Using a series of LED's aligned along a 15.5 meter rail to simulate a pitched baseball, participants swung the bat while photocells captured the timing of the swing. The participants were required to hold their mean absolute error of twenty swings within thirty milliseconds at two simulated pitching velocities (36m/s and 28m/s) presented at random. Being that no ball was contacted by the bat, feedback of his performance was given orally, via knowledge of results, of whether they were 'early' or 'late' and an approximation of the quantitative value (+/- in milliseconds) of how early/late the swing was (Matsuo, Kasai, & Asami, 1993). Baseline values were compared with data that was obtained after a full month of experience to the methodology of the testing process.

Results revealed that the task in which the swinging movement had to be performed with an absolute error less than thirty milliseconds was difficult to achieve quickly under either velocity condition (Matsuo, Kasai, & Asami, 1993). However, all participants could improve their performance faster at a slow target than at the fast target velocity depending upon the strategy they employed (Matsuo, Kasai, & Asami, 1993). Results showed that initiating the swing earlier, then fine-tuning the movement time to the pitch velocity appeared to be the best way to

improve and is the primary factor for improvement under insufficient time and unsettled conditions; also, compensation for premature swings by lengthening the movement time cannot go overlooked, and is also a crucial factor (Matsuo, Kasai, & Asami, 1993).

Expanding upon and supporting the work of Matsuo, Kasai and Asami, (1993), Matsuo & Kasai (1994) utilized a similar simulated hitting task utilizing LED's to simulate a baseball pitch to obtain information of the timing strategy of baseball hitting. The main finding was that the initial movement occurred at approximately the same time regardless of the variation of the velocity of the simulated pitch and personal preference or hitting style (Matsuo & Kasai, 1994). Furthermore, variability in the timing of bat and body segment movements was observed early, however the acceleration of the bat to maximum velocity occurred very close to 'impact' and was similar across all participants regardless of personal preference or hitting style (Matsuo & Kasai, 1994). The previous two studies are unique when compared to others presented being that it was a simulated pitch using LED's; however, it further supports circumstantial notions that the best hitters possess a fundamental mechanism that affords the hitter to effectively make contact despite an assortment of personal preferences of hitting approaches, styles or stances (Matsuo & Kasai, 1994).

Variables such as personal preference of hitting approaches, hitting styles, variation between batting stances or experience may impact the attainment maximum swing velocity prior to contact. McLean & Reeder (2000) conducted a study investigating upper extremity kinematics of dominate and non-dominate side hitting. The authors studied eleven collegiate baseball players whose selection was based on their ability to successfully perform a hitting movement from both sides of the plate (switch hitter). Like previous studies discussed, a video camera sampling at 60Hz was hung above the hitter to capture the hitter performing swings in the transverse plane while making contact with a baseball aligned with the midpoint of the hitters sternum (McLean & Reeder, 2000), which coincides with the upper limit of the strike zone as defined by NCAA and Major League baseball rules. The subjects were asked to complete the Bryden's (1977) simplified Edinburgh Handedness Inventory to assess hand dominance.

Results of the study found that there was no significant differences in impact bat velocity between hitting from dominate and non-dominate side or maximum angular velocities between dominate and non-dominate side (McLean & Reeder, 2000). Right hand dominate hitter achieved similar bat velocities from the right and left side of the plate and achieved significantly higher maximum elbow

angular velocity when hitting from the dominate side. Left handed dominate hitters achieved similar bat velocities from the right and left side of the plate and had no significant differences in upper extremity kinematics when hitting from either side of the plate (McLean & Reeder, 2000). When hitting from the right side of the plate, right hand dominate hitters achieved a significantly greater maximum elbow angular velocity than left hand dominate hitters while left hand dominate hitters achieved a significantly greater shoulder angular velocity than right hand dominate hitters (McLean & Reeder, 2000). No significant differences were observed between right handed and left handed dominate hitter when hitting from the left side of the plate. The results support that hitting kinematics were dependent, but that these differences did not result in an overall decrease in performance in the mechanical aspects of the swing (McLean & Reeder, 2000).

Investigating the effects of various batting stances on ground reaction forces, bat velocity, and response time, LaBranche (1994) conducted a study utilizing seventeen members of the Springfield College baseball program. Bat velocities at the point of ball-bat contact were measured by a uniaxial video analysis system capturing in two-dimensions, while peak anteroposterior forces for the rear foot were measured by a force platform and response times were measured by a time lapse clock. The participants were instructed to hit from a

stationary batting tee while each hitter was tested using either a closed, square, and open batting stance. Results showed no significant mean differences found for bat velocity or between square and closed stance for ground reaction force and response time (LaBranche, 1994). However, for reaction forces, the square and closed stances were significantly greater than the open stance while response time for these stances were significantly less demonstrating that the open stance produced a slower swing velocity than a square or closed stance (LaBranche, 1994). The authors concluded that baseball hitters tend to produce slower, less powerful swings when they assume an open stance.

In one of the first studies to utilize three-dimensional motion analysis, Welch, Banks, Cook and Draovitch (1995) established a comprehensive investigation on the biomechanical description of hitting a baseball to provide an inclusive understanding of the body's natural coordination during the baseball swing. Participants in this study were thirty-nine (25 right handed hitter and 14 left handed hitters) male professional baseball players. To maintain uniformity among the participants, only right handed hitters were selected who had at least one-hundred at bats with a minimum batting average of .250. A total of twenty-three reflective markers were placed at various locations on the hitter, bat, and baseball of seven professional right handed hitters for

data collection as they hit a baseball off of a standard batting tee. The movements of the reflective markers were tracked via a six camera motion analysis system sampling at 200Hz. The global reference frame was defined as the three-dimensional coordinate system in which the relative movement of the body was measured (Welch et al., 1995). The positive X direction was defined as the direction from home plate to the pitching rubber, which was the most crucial because it was used as a reference for the segment rotation and stride parameters, while positive Z was defined as pointing superiorly and the positive Y was defined as pointing to the left (Welch et al., 1995).

The batting tee was adjusted to the hitters preferred position and to a height consistent with hitting a line drive up the middle (directly over the pitcher). The hitter was then instructed to hit the ball marked with reflective tape for data collection. The three best line drive hits were used for data analysis. Temporal events of the batting movement was broken down into 3 phases: lead foot off (the ground), lead foot down (contact back to the ground), and ball contact (Welch et al., 1995). Kinematic variables were defined as stride length and direction, flexion and extension of the left and right knee as well as the left and right elbow, segment rotation of the hips, shoulders and arms and movement of the bat described as bat lag (Welch et al., 1995). Stride length specifically defined as the distance between the left and

right toe at lead foot contact with the ground, while stride direction was specifically defined as the angle formed between the vector from the right to left toe and the global X axis (Welch et al., 1995). Flexion and extension was specifically defined as the absolute angle formed between the proximal and distal segments comprising the joint (Welch et al., 1995). Segment rotation for the hips was specifically defined as a vector from the right hip to the left hip; the shoulders were specifically defined as a vector from the right shoulder to the left shoulder and the arms as a vector from the mid-shoulders to the mid-wrists (Welch et al., 1995). Finally, bat lag was specifically defined as the absolute angle formed between the vector representing the bat from the handle to the barrel and the vector from the mid-shoulders to the mid-wrists (Welch et al., 1995).

Starting with lead foot off of the ground, which occurred at -570 milliseconds relative to ball contact (Fortenbaugh, 2011; Welch et al., 1995), the biomechanical description began with an explanation of the coiling phase which included a weight shift toward the right (back) leg and at approximately the same time, the upper body rotated in a clockwise direction (toward the catcher) around the axis of the trunk, initiated by the arms and shoulders and followed closely by the hips (Welch et al., 1995). During this coiling phase, the arms which initiated the clockwise rotation, had rotated to 150° at foot off, while the

shoulders had rotated to 30° followed by the hips at 18° (Welch et al., 1995). As the stride continued forward toward foot contact with the ground, the hips rotated to a maximum position of 28° at approximately -.350 seconds prior to ball contact while the hips began to rotate counterclockwise (toward the pitching rubber) (Welch et al., 1995). However, the shoulders continued clockwise increasing the coil of the trunk segment until they reached a maximum rotation of 52° at approximately -.265 seconds prior to contact (Welch et al., 1995). At that moment, they followed the hips in a counterclockwise rotation toward the ball. However, the arms, at the same time continued in a clockwise rotation around the axis of the trunk, thus effectively further increasing the coil of the upper body against the movement of the hips and shoulders (Welch et al., 1995).

Following contact with the left foot to the ground, which dictates the movement as being a closed energy transfer, the mean stride length was 85 centimeters (380% of hip width) with a stride direction of 12° (closed) and a position, as the foot began to make contact with the ground of 67° (Welch et al., 1995). At this time, the arms, which have been increasing the coil of the upper body by continuing in the clockwise direction, reached a maximum position of 185° and began a counterclockwise rotation (Welch et al., 1995). With a weight shift forward, segments were accelerated to maximum velocities as the

body coordinated an effort to produce bat speed. The left leg extended at the knee pushing the left hip backward, while the right leg pushed the right hip forward creating a counterclockwise acceleration of the hips around the axis of the trunk (Welch et al., 1995). Increases in rotational velocity of the hip were observed until a maximum velocity of $714^{\circ}/\text{second}$ at approximately $-.075$ seconds prior to contact while the arms and shoulders, following the lead of the hips, accelerated to a maximum rotational velocity of $1160^{\circ}/\text{second}$ and $937^{\circ}/\text{second}$, respectively at approximately $-.065$ seconds prior to contact (Welch et al., 1995).

As a result of the body's coordination, the bat also moved about the axis of the trunk increasing in both angular and linear velocity. The anterior movement of the bat away from the body increased to a velocity of 19 meters/second at approximately $-.04$ seconds prior to contact, while the downward movement increased to a maximum velocity of 16 meters/second (Welch et al., 1995). Approaching the point of contact, the hitter utilized the remaining amount of angular speed along with the kinetic link as the speed of the bat lag (uncocking) reached its maximum value of $1588^{\circ}/\text{second}$ approximately $-.020$ seconds prior to contact (Welch et al., 1995). The bat then reached its maximum linear velocity of 31 meters/second in unison with the right arm maximum extension velocity of $948^{\circ}/\text{second}$,

both occurring at approximately -.015 seconds prior to contact (Welch et al., 1995). This sequence of segmental events, and the decreases in time from the proximal to distal segments, provides strong evidence of the presence of the kinetic chain while performing the baseball swing (Welch et al., 1995). Regardless of individual hitting mechanics, the hip segment is accelerated around the axis of the trunk to a maximum velocity which, in turn, increases the velocity of the entire system moving in the intended direction toward the incoming pitch (Welch et al., 1995).

Dragoo (2004) conducted research investigating variables which may contribute to the overall performance of hitting a baseball and to identify those variables within different skill levels to document each variables contribution to an effective swing. Thirty-two participants swung a standardized aluminum bat in a batting cage. Five cameras collecting at 60Hz (Fortenbaugh, 2011) tracked reflective markers to calculate kinematic parameters of angular velocity, linear bat velocity and ball exit velocity from hitters with various levels of experience: youth, high school and college hitters (Dragoo, 2004). Results revealed that there were significant differences between youth and college groups with regard to ball flight time, bat response time, ball exit velocity, linear bat velocity, shoulder angular velocity, hip angular velocity, height, weight, experience level, and age, while *post-hoc*

testing identified there were no significant differences between the high school and college hitters (Dragoo, 2004).

It was established that the highest bat and ball velocities were performed by the collegiate hitters with values of maximum pelvis angular velocity, maximum upper trunk angular velocity, linear bat velocity, and ball exit velocity of 402°/second, 529°/second, 20 meters/second and 57 meters/second, respectively (Fortenbaugh, 2011; Dragoo, 2004). Furthermore, the high school hitters had a somewhat quicker body segment angular velocity; however they obtained lower bat and ball velocities with values of maximum pelvis angular velocity, maximum upper trunk angular velocity, linear bat velocity and ball exit velocity of 470°/ second, 581°/second, 19 meters/second and 48 meters/second, respectively (Fortenbaugh, 2011; Dragoo, 2004). Additionally, the youth hitters had significantly reduced velocities of maximum pelvis angular velocity, maximum upper trunk angular velocity, linear bat velocity and ball exit velocity of 302°/ second, 402°/ second, 15 meters/second and 40 meters/second, respectively (Fortenbaugh, 2011; Dragoo, 2004). Moreover, there were no significant differences in maximum bat angular velocities among college, high school and youth hitters with values of 1199°/second, 1233°/second and 1151°/ second, respectively (Fortenbaugh, 2011; Dragoo, 2004). Being that the high school hitters obtained larger

values of maximum pelvis angular velocity and maximum upper trunk angular velocities, but lower bat and ball velocities identifies the inexperienced skill level with regards to wasted movement during the swing (Dragoo, 2004).

Many studies have examined hitting a ball at the center of strike zone. However, a live pitcher in a game situation does not always attempt to throw the ball down the middle of the plate, toward the hitters' preferred 'hitting zone'. Therefore, it is beneficial to recognize how hitters change their movements to attempt to make contact with the ball at several locations in the strike zone. Tago, Ae, and Koike (2005) investigated the kinematics of the trunk twist angle at different hitting points. Participants consisted of ten right-handed male skilled hitters of a varsity baseball team. Nine hitting areas were set, via a standard batting tee, in the strike zone according to the baseball rules: three heights (high, middle, low) based on the subject's height (letters of the jersey to the knees) and three locations (inside, center, outside) based upon the width of a home plate (Tago et al., 2005). Hitting motion was distributed into six phases by seven instants of motion: take-back start, toe-off, knee high, toe-on, swing start, left upper arm parallel, and impact.

Kinematic data was captured via a Vicon 612 motion analysis system with nine cameras sampling at 120Hz. A trial in which the

fastest ball velocity and good feeling of the participant was obtained and chosen for each specific hitting area was used for analysis. A trunk twist angle was defined as the angle between a line connecting the hips and a line connecting the shoulders, which were projected on a horizontal plane (Tago et al., 2005).

Results of this study showed that shoulder rotation to the opposite hitting direction, (toward the catcher), was significantly larger in the low ball hitting from swing start to left upper arm parallel than that of the high ball hitting, and the shoulder forward rotation was significantly smaller in the low ball hitting at impact than that of the high ball hitting (Tago et al., 2005). Lastly, changes in trunk twist angle for hitting the ball at three areas (outside, center, inside) were shown. The shoulder backward rotation was larger in the outside ball hitting from toe-on to left upper arm parallel than that of the inside ball hitting, and the shoulder forward rotation tended to be smaller in the outside ball hitting at impact than that of the inside ball hitting; however, they were not significant (Tago et al., 2005). These results suggest that when attempting to hit a baseball in the upper part of the strike zone, the hitter should rotate the shoulders in a clockwise (toward the catcher) direction in a small range from the start of the swing to left upper arm parallel, but use a large counterclockwise (toward pitcher) rotation from left upper arm parallel to contact (Tago et al., 2005). However, when

attempting to hit a baseball in lower part of the strike zone, the opposite approach should be adopted where the hitter uses a large clockwise rotation of the shoulders from toe-on to left upper arm parallel then a small forward counterclockwise rotation from left upper arm parallel to impact (Tago et al., 2005). Although insignificant findings were presented, the changes observed are important because it delineates body movements for inside and outside pitch hitting.

Further delineation of how a hitter uses various grips on the bat should also be assessed to understand the changes in movement patterns with different grips. In certain situations, such as when a hitter has two strikes against him, a hitter must “choke up” on the bat (moving the hands closer to the barrel). It is commonly believed among baseball coaches and hitters that choking up on the bat provides both biomechanical (e.g., quicker bat and more compact swing) and psychological (e.g., enhances a hitter’s concentration and they get “fooled” less) advantages (DeRenne & Blitzbau, 1990; Escamilla et al., 2009). In addition, many believe that choking up on the bat provides more bat control and bat velocity (the bat feels lighter), resulting in more accuracy at contact (DeRenne & Blitzbau, 1990; Escamilla et al., 2009). It is in this specific situation where Escamilla et al., (2009) investigated the effects of bat grip on baseball hitting kinematics. Fourteen adult baseball players (eight collegiate and six professional)

served as participants for this study. Two synchronized, motion analysis video cameras sampling at 120Hz were positioned to view the hitter while each hitter completed 10 hard, full-effort swings with a normal grip (hands as far down as possible on the bat) and 10 hard, full-effort swings with a choke-up grip (6.35cm closer to the barrel) as a pitching machine 'pitched' balls to them during their normal batting practice (Escamilla et al., 2009) with the goal to hit a line drive which travel 225ft to left-center field.

Escamilla et al., (2009) defined the swing as having four events and three phases. The first event was 'lead foot off ground,' representing the beginning of the stride phase. Next, 'lead foot contact with ground,' which represented the end of the stride phase. 'Lead foot off ground' to 'lead foot contact with ground' represented the time duration of the stride phase of the swing. The third event was 'hands started to move forward.' 'Lead foot contact with ground' to 'hands started to move forward' represented the duration of the transition phase of the swing (transition between the stride phase and acceleration phase), while the last event was 'bat-ball contact,' which was defined as the first frame immediately before bat-ball contact (Escamilla et al., 2009).

Results showed that that compared with using a normal grip, using a choke-up grip resulted in significantly less time during the

stride phase and during the swing (Escamilla et al., 2009). Next, compared with using a normal grip, using a choke-up grip resulted in greater left elbow flexion at lead foot contact with ground and greater right elbow flexion at lead foot contact with ground (Escamilla et al., 2009). Moreover, compared with using a normal grip, using a choke-up grip resulted in a significantly smaller upper torso angle (open position-rotation toward the pitcher) at lead foot contact with ground and significantly smaller pelvis angle (closed position- rotation toward the catcher) at bat-ball contact, while the range of motion of the upper torso and pelvis during the swing was significantly greater using the normal grip compared with using the choke-up grip (Escamilla et al., 2009). Furthermore, compared with using the normal grip, using the choke-up grip resulted in greater peak right elbow extension angular velocity while bat linear velocity at bat-ball contact was significantly greater using a normal grip compared with using a choke-up grip (Escamilla et al., 2009).

Decreased time spent in the stride phase while utilizing the choke-up grip when compared to the normal grip infers that hitters speed up the stride when choking-up, but sustain similar stride length when being compared to the normal grip, which effectively decreases the moment of inertia (MOI) by increasing the mass to an area that is closer to the axis of rotation (the hands) (Escamilla et al., 2009). The

reduced MOI while choking-up may lead to faster movements, which was observed with greater peak right elbow extension angular velocity, however it may lead to a decrease in force production (force velocity relationship), which may explain the reason for the approximately 10% decrease in linear bat speed at contact when comparing to a normal grip (Escamilla et al., 2009).

When choking up, the batter adjusted his swing mechanics to be quicker using less contribution of the trunk, increased contribution from the arms, but sacrificed potential gains in bat velocity (Escamilla et al., 2009). The increased linear bat velocity at contact when utilizing the normal grip may be surprising to players who have been taught that choking-up would speed the bat up, which would result in an increase in bat velocity. Linear bat velocity was decreased when using the choke-up grip even with bat mass remaining constant, these data indicate that choking-up affects the 'effective mass' of the bat which would result in a decrease in momentum ($\text{mass} \times \text{velocity}$) transfer from bat to ball while implementing the choke-up grip (Escamilla et al., 2009).

From a biomechanical standpoint, the findings by Escamilla et al., (2009) are similar to the biomechanical description of the hitting movement presented by Welch et al., (1995). It was supported that a hitter is likely to keep the left elbow (lead elbow for right handed hitter)

extended with a more flexed right elbow, which is consistent with the work conducted by Welch et al., (1995), throughout the stride and swing phase being that the right elbow flexed approximately double the amount of the left elbow (Escamilla et al., 2009). Furthermore, the upper torso maintained a more closed position when compared with the pelvis and reached a higher peak angular velocity when compared to the pelvis, while the peak angular velocity obtained by the upper torso transpired later in the swing when compared to peak angular velocity of the pelvis (Escamilla et al., 2009). This infers a sequencing of segments as the swing progresses toward contact which occurred in the normal and choke-up grip (Escamilla et al., 2009). The finite time between peak angular velocities of the pelvis and upper torso denotes that utilizing varying bat grips does not affect the sequential timing that occurs throughout the swing (Escamilla et al., 2009). The authors concluded that the observed decrease in the stride phase when using the choke-up grip implies that hitters speed up the movement during that phase of the swing when they choke-up. Although there were not temporal significance in the acceleration phase between grips, the total time of the swing was significantly less when utilizing the choke-up grip, which supports the anecdotal theory that a choke-up grip results in a 'quicker' swing (Escamilla et al., 2009).

However, linear bat velocity was decreased when utilizing the choke-up grip, possibly due to the difference in mass distribution of the bat (Escamilla et al., 2009) which could result in decreased distance of the ball post-impact. This decreased distance may be attributed to a diminished force production in accordance with the force-velocity relationship for muscle contraction, being that a greater right elbow extension velocity using the choke-up grip when compared to the normal grip (Escamilla et al., 2009). Secondly, when choking up, the bats length is reduced, thus bringing the distal portion of the bat closer to the axis of rotation located around the wrists resulting in the bat traveling slower when being compared to the normal grip.

After looking at differences in grip, Escamilla et al., (2009) investigated the kinematics of the baseball swing between age levels. Twenty-four participants were recruited for this study. Twelve participants were youth right-handed hitters where the remaining twelve were adult right-handed hitters, six collegiate hitters and six professional hitters. All youth hitters were all-star hitters in youth league with batting averages above .300, which according to youth baseball standards classified them as 'good' or 'skilled' hitters (DeRenne et al., 2008; DeRenne, 2007; Race, 1961; Escamilla et al., 2009). All adult hitters also had batting averages above .300, which according to college and professional baseball standards classified

them as 'good' or 'skilled' hitters (DeRenne et al., 2008; DeRenne, 2007; Race, 1961; Escamilla et al., 2009). Each youth and adult hitter completed 10–15 hard, full-effort swings with a normal grip (hands as far down as possible on the bat) as a pitching machine “pitched” balls to them during their normal batting practice. All pitches were between 32.6 and 33.5 meters/second (73–75 mph) for adult hitters and 28.2–29.1 meters/second (63–65 mph) for youth hitters, based on age-appropriate velocities of normal batting practice for youth and adult hitters (DeRenne et al., 2008; DeRenne, 2007; Race, 1961; Escamilla et al., 2009) while two synchronized, motion analysis video cameras sampling at 120Hz captured the hitting movement.

The swing was defined by four events and three phases, exactly the same as the study performed by Escamilla et al., (2009) when they investigated the differences of the choke-up and normal grip. Results showed that when compared with youth hitters, adult hitters took significantly greater time during the stride phase and during the swing (Escamilla et al., 2009). Next, when compared with youth hitters, adult hitters flexed the lead (left) knee significantly more when the hands started to move forward. As a result, adult hitters flexed the lead knee over a greater range of motion during the transition phase (31° versus 13°) and extended the lead knee over a greater range of motion during the bat acceleration phase (59° versus 32°) (Escamilla et al., 2009).

Furthermore, when compared with youth hitters, adult hitters maintained a more open pelvis position at lead foot off ground. In addition, adult hitters maintained a more open upper torso position when the hands started to move forward and a more closed upper torso position at bat-ball contact (Escamilla et al., 2009).

Moreover, when compared with youth hitters, peak upper torso angular velocity in adult hitters was significantly greater and occurred significantly later in the bat acceleration phase; additionally, when compared with youth hitters, peak left elbow extension angular velocity and peak left knee extension angular velocity was significantly greater in adult hitters during the bat acceleration phase (Escamilla et al., 2009). Finally, when compared with youth hitters, bat linear velocity at bat-ball contact was significantly greater in adult hitters (Escamilla et al., 2009).

These significant differences presented between youth and adult hitters should not be surprising due to the fact that adult hitters were on average 7.5 years older, 35–40% heavier, and 5% taller and used bats that were 15% heavier and 5% longer (Escamilla et al., 2009). It is likely that this maturation of the adult hitters compared with the youth hitters resulted in the significant differences because the stronger and relatively bigger or more massive, adult hitters had an increased ability to generate larger angular velocities and linear bat

velocity at contact (Escamilla et al., 2009). Despite the significant differences, adult and youth hitters spent nearly the same amount of time in the transition and bat acceleration phase, however adult hitters spent approximately 40% more time in the stride phase, which is consistent with the work done by Welch et al., (1995) but slightly less time in the transition and bat acceleration phase (.18 seconds) when compared with the study conducted by Escamilla et al., (2009) with a value of .21 seconds.

The increase in time spent during the stride phase for adult hitters compared to youth hitters suggests that the adult hitters increase the time 'loading up' during the preparation for the swing phase. 'Loading up' is imperative in producing energy in the lower half of the body (legs and trunk) that is transmitted up the kinetic chain to the upper extremities, then to the baseball bat (Messier & Owen, 1985; Messier & Owen, 1986; Escamilla et al., 2009). In regards to the similar linear and angular displacement parameters (stride length and elbow, knee, upper torso, and pelvis angles) between the two groups suggests that the mechanics of performing the hitting motion are similar in many aspects among various age levels, however in other aspects of the hitting motion, significant differences in angular and linear velocities delineates between youth and adult hitters (Escamilla et al., 2009).

Kinematic similarities between skilled youth and adult levels have also been demonstrated in baseball pitching (Fleisig et al., 1999) by reporting that many linear and angular displacement parameters were not significantly different between youth and adult pitchers which are consistent with the current study done by Escamilla et al., (2009). However, in contrast, many linear and angular velocities in pitching were significantly different, which is also similar to the work done by Escamilla et al., (2009). From these data presented, skilled adult hitters and pitchers move body segments faster than skilled youth hitters and pitchers, but segmental and joint angular positions are similar between skilled adult and youth hitters, as well as between skilled adult and youth pitchers (Escamilla et al., 2009; Fleisig et al., 1999).

Welch et al., (1995) first established that hitters tend to keep their lead elbow (left elbow for right-handed hitters) straighter than their rear elbow, where throughout the stride and swing phases, the rear elbow was flexed nearly twice as much as the lead elbow which also agrees with Escamilla et al., (2009) when looking at differences between the choke-up and normal grips. Furthermore, McIntyre and Pfautsch (1982) reported significant differences between same and opposite field hits, with hits to the same field (left field for a right-

handed hitter) resulted in increased lead elbow extension when compared with swings to the opposite field.

Lastly, Welch et al. (1995) reported sequencing of pelvis and upper torso rotation, which was observed in the current study done by Escamilla et al., (2009). Throughout the duration of the swing, the upper torso stayed in a more closed position (more rotation towards the catcher) and attained a greater peak angular velocity when compared to the peak angular velocity of the pelvis. This sequencing was also observed in the study of choke-up and normal grips conducted by Escamilla et al., (2009). Moreover, peak angular velocity of the upper torso transpired later in the swing compared with the peak angular velocity of the pelvis, which indicated a sequencing of movements which occurred in both the youth and adult hitters. Peak angular velocities gradually increased and transpired later in the swing phase up the chain from the knee, pelvis, upper torso, elbows and then terminating with the arms which is in agreement with the kinetic link principle, which increased linear bat velocities (Escamilla et al., 2009; Welch et al., 1995).

The later occurring and significantly higher peak upper torso angular velocity in the adult hitters facilitated the higher peak left elbow angular velocity and subsequently the increased linear bat velocity at contact for the adult hitters. The authors conclude that despite the

similarities, there were several differences in the kinematic and temporal parameters between the two cohorts, which suggest that the hitting mechanics are dissimilar between these two groups of hitters (Escamilla et al., 2009).

2.1.2 Electromyography (EMG) Studies of the Baseball Swing.

Many studies have investigated the kinematics and kinetics of the baseball swing, however, there is a paucity of research conducted investigating the intricacies at the muscular level via electromyography to measure muscle activation while performing a complex movement such as the baseball swing. An early study investigating the electromyography realm of the baseball swing was conducted by Kitzman (1964). He strived to examine, in skilled and unskilled hitters, muscular involvement and function of various muscles such as: right and the left pectoralis major muscles (clavicular heads); the right and the left triceps brachii muscles (lateral and long heads); and the right and the left latissimus dorsi muscles via surface EMG during the baseball swing. The hitters who participated in this study were four men; two right-handed professional baseball players and two right-handed freshman students who did not participate in a collegiate baseball regimen.

Results, albeit sparse, revealed that the aforementioned muscles of interest were active rather early in the swing, while muscles which were not investigated adopted activity as the swing progressed (Kitzman, 1964). The authors concluded increased strength in the left triceps brachii muscles, specifically the long heads of the muscle, could increase the force imparted onto the bat during the hitting motion (Kitzman, 1964). This finding is consistent with Welch et al., (1995) and his biomechanical description of the baseball swing which revealed that elbow extension is a vital part of the swing and Escamilla et al., 2009 when looking hitting kinematics between skilled young and adult hitters where peak elbow angular velocity discriminated between the hitters.

As cited in work conducted by Fortenbaugh (2011) and Shaffer, Jobe, Pink, and Perry (1993), two studies focusing on EMG were conducted by Broer and Houtz (1967) and Kauffman & Greenisen (1973) introduced early studies looking at EMG during the baseball swing. Broer and Houtz (1967) performed an EMG analysis on seventeen upper extremity, fourteen lower extremity and three trunk muscle groups using surface EMG methods in one unskilled hitter. Although results were not presented quantitatively, their analysis brought to light the significance of muscle activation in the abdominal

muscles which acted as stabilizers to the trunk segment while performing a baseball swing.

Kauffman & Greenisen (1973) utilized surface EMG electrodes to examine the muscular activity of the long heads of both the biceps and triceps muscles of four collegiate baseball players under two conditions (weighted and unweighted bats). Their results found no indication of an advantageous effect when swinging a weighted bat prior to stepping into the batter's box to face live pitching. Relative to the previous studies, a more recent investigation conducted by Shaffer et al., (1993) systematically examined the electromyography of twelve muscles of eighteen professional baseball players while performing the baseball swing. Utilizing the Basmajian technique, fine wire electrodes were inserted into the supraspinatus, long head of the triceps, posterior deltoid and middle serratus anterior at the sixth rib of each hitters lead (closest to the pitcher) arm and the lower gluteus maximus of their back (closest to the catcher) leg. Simultaneously surface electrodes were applied to monitor the activity of the right and left erector spinae, abdominal obliques, vastus medialis obliques, semimembranosus and the long head of the biceps femoris of the back leg. High speed motion picture pictography using 16mm film sampling at 400Hz captured the swing which was broken down into four phases: 'windup,' 'pre-swing,'

'swing' and 'follow through' with 'swing' further broken down into 'early,' 'middle,' and 'late' (Shaffer et al., 1993).

Results for the lower extremity revealed the biceps femoris and semimembranosus were below 50% of the value obtained through manual muscle test (MMT), while during the 'pre-swing' significantly increased to 154% of MMT and 157% of MMT, respectively. Significant decreases in activity were observed in 'early swing' to 100% and 90% of MMT, respectively, while sustained decreases throughout the remainder of the swing to the lowest value of 40% of MMT which was observed in the 'follow through' phase of the swing (Shaffer et al., 1993). Activity for the lower gluteus maximus obtained its lowest value of 25% of MMT during the 'wind-up' phase and significantly increased to 132% of MMT during the 'pre-swing' phase. Activity in the lower gluteus maximus persisted in the 'early swing' phase with a value of 125% of MMT, decreased to 65% of MMT during the 'middle swing,' then further decreased to a value of 45% of MMT in the 'late swing' phase and further decreased in the 'follow through' phase to a value of 26% of MMT. The activity in the vastus medialis obliques significantly increased from 'wind up' phase with a value of 26% of MMT to 63% of MMT in the 'pre-swing' phase, and then increased once again to a peak value of 107% of MMT from 'pre-swing' to 'middle swing.'

Through the 'late swing' to the 'follow through' phases, activity decreased from 97% of MMT to 78% of MMT, respectively.

Results from the trunk revealed that both of the erector spinae muscles was low with a value of 42% of MMT during the 'wind-up' phase then significantly increased to a value of greater than 90% of MMT during the 'pre-swing,' 'early swing,' and 'middle swing' phases. A decrease in activity from a value of 98% of MMT in the lead erector spinae and 85% of MMT in the back (trail) erector spinae to significantly decreased levels of 58% of MMT and 68% of MMT, respectively, during the 'follow-through' phase of the swing. Much like the erector spinae muscles, activity of the abdominal obliques revealed fairly low values during the 'wind-up' phase of <30% of MMT. Following the 'wind-up,' a significant increase was observed to a value of over 100% of MMT during the 'pre-swing' phase and lingered throughout the phase. When comparing the erector spinae muscles and abdominal obliques, activity level in the erector spinae muscles showed a statistically significant difference only during the 'follow-through' phase, while the abdominal obliques activity persisted through a range of 101%-134% of MMT in relation to a decreasing erector spinae range of 58%-68% of MMT.

Results from the upper extremity revealed that activity in the posterior deltoid significantly increased from 17% of MMT during the

'wind-up' phase to 101% of MMT during the 'pre-swing' phase. Intensity of the EMG signal significantly decreased through the rest of the swing between 'late swing' with a value of 76% of MMT to 25% of MMT during the 'follow-through' phase. Activity in the triceps during the 'wind-up' phase revealed a low value of 25% of MMT, then significantly increased to a value of 92% of MMT during the 'early' phase and 'middle swing' with a value of 73% of MMT. During the 'middle swing' and 'follow-through' phases, there was a significant decrease in activity to a value of 23% of MMT. Activity of the supraspinatus was fairly low, and remained low throughout the entirety of the swing with a value of 32% of MMT. The lowest activity of the supraspinatus with a value of 13% of MMT occurred during the 'wind-up' phase, which showed significantly less activation than the 'pre,' 'mid' or 'late' phase with a value of 32% of MMT. Much like the supraspinatus, the activity of the middle serratus was low during the entirety of the swing with a value of >40% of MMT, with the lowest value of 18% of MMT during the 'wind-up' phase of the swing which was significantly less activity observed during either the 'middle' or 'late' swing with a value of 39% of MMT for both phases.

During the 'wind-up phase, there were relatively low activity levels observed in the hamstrings of the back leg, which indicated a maintenance of hip extension as the hitter shifted their weight to

prepare for the swing (Shaffer et al., 1993). The 'pre-swing' phase had an increase activity level of the hamstrings and lower gluteus maximus which indicates hip stabilization and the initial instance of power generation (Shaffer et al., 1993). Also, the lead and back erector spinae muscles were active to stabilize the trunk, which is consistent with the results of Broer and Houtz (1967) and allow the transfer of power. Furthermore, during the 'swing' phase, specifically the 'pre' and 'early' swing, activity level of the vastus medialis obliques prohibited the folding of the progressively flexed back leg and augmented push-off to enable a force transfer (Shaffer et al., 1993).

Following the force transfer to the front leg, hamstring and gluteus maximus in the back leg deteriorated while both erector spinae muscles and obliques continued to have a high activity level throughout the swing, however erector spinae activity diminished prior to contact which indicates the importance of the trunk segment as the body uncoils from a counterclockwise rotation toward the direction of the pitch (Shaffer et al., 1993). As the swing progressed, activity was decreasing yet the relatively high activity levels in the posterior deltoid and triceps suggests a positional role but may contribute to power generation (Shaffer et al., 1993), however, gradual decreases in activity may suggest these muscles are not the primary source for power production. The authors concluded hamstrings and gluteus

maximus activation contribute significantly to establish a solid base and power generation when the torso 'uncoils' during the swing (Shaffer et al., 1993). Furthermore, the hitting motion of skilled hitters relies on coordinated activation from the lower extremities, to the trunk and finally terminating with the upper extremity (Escamilla et al., 2009; Welch et al., 1995), while activity of the muscles examined in the upper extremity is a vital part to position the bat during the swing (Shaffer et al., 1993).

2.1.3. Kinetic Studies of the Baseball Swing

As reported above, a biomechanics analysis of hitting a baseball conducted by Welch et al., 1995 also included kinetics (application of force by each foot to the ground relative to the global reference frame) of the baseball swing by examining the ground reaction forces (GRFs), center of mass (COM) and center of pressure (COP). The global reference frame was defined as the X axis pointed from home plate to pitching rubber, the Z axis pointed up towards the hitters head, and the Y axis pointed orthogonally from the Z and X axis (Welch et al., 1995). Utilizing two, six channel force plates sampling at a rate of 1000Hz, three-dimensional ground reaction forces were measured for each foot. Movement of the COP between the two feet and the bodies COM in the global X direction (toward the pitching rubber) was used as an

indication of dynamic balance and forward momentum (Contini, 1972; DeRenne, Stellar & Blitzbau, 1993; Welch et al., 1995).

Results from the foot off/stride phase of the swing revealed that immediately following the initiation of the 'coiling' movement (rotation towards the catcher), the left (front) leg was raised, breaking contact with the foot and ground (foot off) which resulted in an increase of the total force applied by the back leg to a value of 102% of bodyweight (Welch et al., 1995). GRF's showed that part of the total force applied was shear force in the global X and Y directions, with the shear force encouraging linear and rotational movement to the hitter. At foot off, the right foot produced 146N of shear force in the $-X$ direction and 26N in the Y direction while the right knee was flexed to a value of 32° and the COP moved to the $-X$ direction toward the right foot, 20 centimeters behind the COM (Welch et al., 1995).

During the foot contact phase, weight was shifted forward as the heel made contact which applied a total force equal to 123% of bodyweight to the ground (Welch et al., 1995). As part of the total force applied, 292N of shear force was observed in the X direction and 280N of shear force in the $-Y$ direction. Total force produced at the right foot had decreased to a value of 58% of bodyweight (Welch et al., 1995), as part of that force, the right foot applied 80N of shear force in the $-X$ direction and 184N of force in the Y direction, while the COP made an

extreme shift forward in the X direction 20 centimeters ahead of the COM (Welch et al., 1995). Weight shift in the forward direction (toward pitcher) along with the shear forces afforded the acceleration to maximum velocities as the hitter made a coordinated effort to produce maximum bat speed. At contact, the body utilized coordination and position to produce bat velocity and position (Welch et al., 1995). The hitters' lead (left) leg was flexed 15° at the knee, which was acting as a brace, applying a total force onto the ground equivalent to 84% of bodyweight; while, the right leg was flexed 45° at the knee, which was acting as a support, applying a total force equivalent of 16% of bodyweight (Welch et al., 1995).

The linear component (X direction) was the forward movement of the hitter preparing to contact the incoming ball. By allocating weight to the back leg/foot, the COP moves behind the COM in the global X direction, resulting in the COM being ahead of the COP. This movement of the COP disrupts the equilibrium state of the body where the COP and COM are aligned causing the body to 'motivate' toward the direction of the COM (Welch et al., 1995). This gravitation towards the COM, along with the shear forces produced by the rear foot in the X direction, is what drives the hitter to exploit a linear movement towards the incoming ball (Welch et al., 1995). However, when the lead foot makes contact with the ground, the linear and rotational

components begin to interact with each other and it is this interaction which will dictate whether a linear or rotational kinetic link movement will be exploited.

As previously stated, when the lead foot came into contact with the ground, the COP moved ahead of the COM and both feet applied a shear force which produces a force couple at the hip segment enabling a counterclockwise rotation about the axis of the trunk (Welch et al., 1995). At this instant, the hitter has a choice to exploit either a linear or rotational movement. If the hitter chooses to utilize a rotational movement, the COP will align with the COM between the hitters' feet. This alignment allows both feet to contribute shear forces which subsequently increases the force couple applied to the hip segment (Welch et al., 1995); however, if the hitter chooses to exploit a linear movement, the COP remains in a location near the lead foot and the COM gravitates forward to align with the COP located under the lead leg. This alignment reduces the force couple at the hip segment by decreasing the shear forces by the feet because only the lead foot is applying the significant shear force, instead of both feet when rotational movement is utilized (Welch et al., 1995).

Yanai (2007) investigated a mechanical cause of body rotation about the vertical axis in baseball hitting utilizing twenty members of collegiate varsity baseball team while performing 'toss batting' (Yanai

(2007). 'Toss batting,' which is essentially a 'soft toss,' where the ball was tossed toward the ball-impact zone of the hitter by another player kneeling on the ground. 'Toss batting' occurred approximately three meters away from the subject in the Motion Analysis Laboratory. With each foot on a force platform, the participant hit the ball toward a net located at the same field beside the person tossing the ball toward the hitter. Unlimited practices were given to allow the participant to become familiar with the methodology, then five trials of 'toss batting' were utilized for data collection.

The mechanical cause of the body's rotation about the vertical axis passing through the COM was divided into four components; the moment of the ground reaction force acting on the front leg around the COM (M_f), the moment of the ground reaction force acting on the back leg around the COM (M_b), the free moment acting on the front leg (F_f), and the free moment acting on the front leg (F_b) (Yanai, 2007). Results showed angular momentum of the hitters body was close to zero at front leg touchdown then increased considerably at the instant of contact (Yanai (2007). Contribution of the moment of the ground reaction force acting on the front leg around the COM was found to be the largest value, followed by the moment of the ground reaction force acting on the back leg around the COM; with a negative contribution of

the free moment acting on the front leg, and the free moment acting on the front leg (Yanai, 2007).

The results indicated the rotation of the hitters' body, while performing the hitting motion, was produced largely by the moment of the ground reaction forces acting on the legs around the COM. Specifically, the maximum ground reaction force was generated by the lead leg, which in turn generated the main turning effect to the hitters' body (Yanai (2007)). Furthermore, total angular momentum produced by the ground reaction forces and free moments at the lead leg was found to be significantly greater than that of the trailing leg. The authors concluded that the front leg acts as the major contributor of body rotation of the hitter (Yanai (2007)). This contradicts the findings of Welch et al., (1995) where less force produced by the lead leg resulted in a decrease in the force couple at the hip segment, which produced a linear rather than rotational movement by the hitter.

In a previously reported study of kinematic variables which might contribute to the overall performance of hitting a baseball conducted by Dragoo (2003), kinetic data was also collected. Utilizing force plates sampling at a rate of 120Hz to obtain kinetic parameters of: center of pressure data, which also yielded spike of accelerations (based on velocity of COP) and location of last spike relative to ball

contact were collected on youth, high school, and college hitters, for which comparisons between the groups were made.

Results revealed that that there were significant differences between little league and college groups with regard to COP in the X and Y direction, while post-hoc testing identified there were no significant differences between the high school and college (Dragoo, 2003). Across all three skill levels, with regards to experience level, significant differences were identified between COP in the X and Y directions, bat response time, ball flight time and location of last spike was significantly related to ball exit velocity. As cited in the work conducted by Fortenbaugh (2011), it was revealed that there were significant differences in response time and total excursion of COP in the X and Y directions (the X axis pointed from home plate to the pitching rubber). Furthermore, within the college group it was identified that there was an extended period of bat response time despite swinging at the fastest pitches, while in the high school group it was identified that athletes with a higher bat response time also had the highest ball exit velocity (Dragoo, 2003).

Specific values for the work conducted by Dragoo (2003) were obtained from Fortenbaugh (2011), which revealed college hitters had the longest delay in response time with a value of 198 milliseconds, while high school hitters had an earlier initial reaction with a value of

190 milliseconds and youth hitters were even earlier with a value of 177 milliseconds. The longer decision time afforded the collegiate hitters' to allow more time to decide whether or not to swing, or how to approach the incoming pitch if the decision to initiate the swing was made. Moreover, Fortenbaugh (2011) obtained specific values from Dragoo (2003), of COP excursion between college, high school and youth hitters. He reported college hitters, compared to high school and youth, respectively, also had the greatest total COPx excursion (50 millimeters, 39 millimeters, 28 millimeters) and total COPy excursion (189 millimeters, 170 millimeters, 81 millimeters). With the decreased values in millimeters indicating that the collegiate hitters had the greatest weight transfer, followed by the high school hitters then the youth hitters (Fortenbaugh, 2011; Dragoo, 2003). Dragoo (2003) concluded that the kinetic data identified that COPy increased as skill levels improved. These values are consistent with the work conducted by Welch et al., (1995) which revealed a weight shift, as presented in a value of percent bodyweight, occurred to aid in the generation of maximum bat velocity.

Katsumata (2007) investigated a functional modulation for timing a movement: a coordinative structure in baseball hitting. Six, right-handed collegiate baseball players volunteered as participants for the study. Participants performed the hitting motion while standing on

two force platforms which were fixed to the ground in the location of the batter's box to record vertical ground reaction forces. A pitching machine was positioned 18.44 meters away from the hitter, which is in accordance with the distance between the pitching rubber and home plate at the collegiate level. The pitching machine 'threw' balls at two different speeds: fast (32.2 meters/second) and slow (20.3 meters/second), after the hitter was instructed to address pitches with their own hitting stances by placing one foot on each force platform and hitting pitches delivered by the pitching machine (Katsumata, 2007). This experiment consisted of three sessions. The first session consisted of the hitters being subjected to fast pitches while the second session consisted of slow pitches. Since the first two sessions (mono-pitch) (Katsumata, 2007) had predictable speeds where the hitter could acclimate themselves to the speed at which the ball is approaching, a third condition consisted of a randomized speed of fast and slow pitches without informing the hitter of the speed of the impending pitch (mix-pitch).

Katsumata (2007) divided the swing into the times of 'stepping,' 'landing,' 'weighting,' 'swing,' and 'peak GRFv after Release and before Impact.' These specific timing variables designate when each successive motion phase (stepping, landing, weighting and swing) transpired relative to release or impact. Results showed, for the

change in GRFv in the hitting movement, that the initiation of the swing started with an increase in GRFv of the lead foot resulting in a decrease in GRFv of the trailing foot, thus indicating a weight shift (Katsumata, 2007), which is consistent with Dragoo (2003) and Welch et al., (1995). Following the initiation, weight was shifted backward which was indicated by an increase in GRFv of the trailing foot and a subsequent decrease in GRFv in the lead foot. Furthermore, results from the temporal pattern of GRFv revealed more similarities than significant differences with the exception of the duration of a bat-swing being significantly shorter in hitting fast pitch than that in hitting slow pitch (Katsumata, 2007). As for the front foot GRFv pattern after landing, the time of landing before impact was longer for a slow pitch than for a fast pitch.

Since there was a significant difference found, a post-hoc analysis was conducted which revealed that the time of landing before impact was longest in mix-slow condition, followed by the mono-slow condition, and no difference was found between mono-fast and mix-fast. The authors concluded that the results demonstrated that there is coordinative structure inherent to the hitting movement for producing a powerful bat-swing and timing it with respect to the flight of a pitch (Katsumata, 2007). Also, baseball batters exploit GRF's for producing a powerful bat-swing by utilizing a weight shift by stepping with a front

foot to the direction of the pitch and transferring the weight onto the front foot (Katsumata, 2007).

Fortenbaugh and Fleisig (2008) conducted a study investigating the ground reaction forces during hitting to add to the limited research of the magnitude and temporal sequencing of swing kinetics, along with the effect of ball/pitch location on swing kinetics. Nine collegiate baseball hitters participated in this study. By use of a batting tee, the strike zone was divided into nine subzones: three heights (high, middle, low) based on the subject's height (letters of the jersey to the knees) and three locations (inside, center, outside) based upon the width of a home plate, which is the areas in which Tago et al., (2005) investigated. The X axis was defined as the axis pointing from home plate towards the pitching rubber, the Z axis was in the vertical direction, and the Y axis was orthogonal to the X and Y axis.

Participants took five swings from each of the nine subzones of the strike zone while standing on two Kistler force plates sampling at a rate of 1250Hz to obtain triaxial GRFs of each foot using force components in all three axes near three events of the baseball swing: initial rock back, forward drive and ball contact which were selected for analysis.

Results revealed that the lead foot had a GRF value of 18% (in the negative X direction) of bodyweight at a time of -1,150 milliseconds prior to ball contact, with the low value of GRF of the lead foot

indicating a weight shift toward the trailing foot (Fortenbaugh, 2011; Fortenbaugh & Fleisig, 2008). The weight which was shifted toward the trailing leg began to gravitate forward to the lead foot with a GRF value of 16% of bodyweight (positive X direction) -407 milliseconds prior to contact (Fortenbaugh, 2011; Fortenbaugh & Fleisig, 2008). At approximately -125 milliseconds prior to contact, the trailing and lead feet acted to stabilize the body with a value of 24% (positive Y direction) of body weight and 32% (negative Y direction) of body weight, respectively (Fortenbaugh, 2011; Fortenbaugh & Fleisig, 2008).

Transfer of momentum via a kinetic chain was observed at -81 milliseconds prior to contact with a peak GRF of 126% of body weight in the positive Z direction and GRFs from the lead and trailing foot with values of 39% of bodyweight (in the negative X direction) and 13% of bodyweight (in the positive X direction), respectively. Furthermore, the results revealed statistically significant differences were found between a limited amount of the kinetic variables (not reported), although the variances were not more than 5% of bodyweight. Fortenbaugh and Fleisig, (2008) concluded that variances exist in the kinetics of the swing with several pitch locations, although additional research should be conducted to include a more realistic hitting scenario with live pitching to obtain more accurate and sport specific results.

2.1.4 Joint Kinetics

In many sports, specifically throwing, hitting and striking movements of the sport, requires that maximum speed is generated at the end of the distal segment in the kinematic chain. Similarly, sports that utilize an implement to maximize end-point velocity such as baseball or tennis demand that the bat or racquet develop maximum velocity prior to contact. This maximum velocity at the distal end of the segment is thought to be produced by the use of a proximal-to-distal sequencing which is defined as the motion that is initiated with the larger, heavier, slower central body segments; then as energy increases, the motion proceeds outward to the smaller, lighter and faster segments (Marshall & Elliott, 2000).

As cited in Marshall & Elliott (2000), Putnam (1993) concisely summarized the description of proximal-to-distal sequencing noting that the concept upon which most others appear to have been developed is the 'summation of speed principle,' the kinetic link principle,' and Plagenhoef's (1971) concept of 'acceleration-deceleration.' In the simplest form, these synonymously associated principles state that to produce the largest possible speed at the end of a linked chain of segments, the motion should start with the more proximal segments and proceed to the more distal segments, with the more distal segment beginning its motion at the same time of the

maximum speed of the proximal one, with each succeeding segment generating a larger end-point speed than the proximal segment (Putnam, 1993; Marshall & Elliott, 2000). There has been numerous two and three-dimensional analyses of throwing and striking activities (for example, Van Gheluwe, & Hebbelinck, 1985; Woo & Chapman, 1992; Sakurai, Ikegami, Okamoto, Yabe, & Toyoshima, 1993) and aspects of a proximal-to-distal sequence have been explored. However, only using the proximal-to-distal sequencing, or any variation of the term, is rather simplistic and may underestimate the complexity of maximizing end-point velocity during an explosive ballistic movement such as vertical jumping, tennis serve or baseball hitting. Contribution of mono and bi-articular muscles and long axis segment rotations has received little attention.

VanIngen Schenau, Bobbert, & Rozendal, (1987) and VanIngen Schenau (1989) explored the unique action of bi-articular muscles. VanIngen Schenau (1989) aimed to clarify the constraints which are associated with the transformation of rotations in joints into the desired translation of the body center of gravity or into the desired translation of a distal segment (i.e. foot, hand) or object (i.e. specifically a baseball bat for the purpose of this study). Utilizing an undisclosed number of skilled subjects, a 16mm high speed camera sampling at 67 frames per second and 100 frames per second, was used to analyze the

movements while performing a cycling movement and vertical jumping movement, respectively. It should be noted for the reader, only the vertical jump will be investigated for the use of this review. The vertical jump illustrates the concept of proximal-to-distal sequencing, along with relative easy way to visualize the large muscles of the lower body during a fairly common human movement (VanIngen Schenau, 1989).

Force plate and EMG data were also recorded simultaneously with kinematic two-dimensional coordinates of specific landmarks. Magnitude, direction and point of force application of reactive forces on the foot were measured via a force plate, while activity of the semitendinosus, gluteus maximus, rectus femoris, vastus medialis, medial head of the gastrocnemius and soleus were measured via EMG. The jumpers were asked to perform two-legged jumps, with a preparatory countermovement while keeping the hands on the hips, for maximum height. Push-off (defined as the phase in which the body center of gravity is accelerated in a vertical direction) begins with the extension of the hip joint at approximately -300 milliseconds preceding toe-off followed by knee extension starting at approximately -200 milliseconds before toe-off and finally followed by an explosive plantar flexion which starts at about -100 milliseconds prior to toe-off (VanIngen Schenau, 1989).

A comparable proximal-to-distal sequence in joint rotations has also been reported for the upper extremity in overarm throwing (Jöris, Edwards van Muyen, van Ingen Schenau, & Kemper, 1985). EMG activity of hamstring and gluteus maximus is increased between -400 and -300 milliseconds followed by an increase in activity of rectus femoris and vastus medialis between -300 and -200 milliseconds while the rate of change of plantar flexor activity is high between -200 and -100 milliseconds (VanIngen Schenau, 1989). It has been debated that the jumper should extend their joints simultaneously to enhance the translational velocity of the body's center of gravity (CoG) (VanIngen Schenau, 1989). Mechanically speaking this may sound reasonable; however, this ignores the transformation of joint rotations into translation of the CoG (VanIngen Schenau, 1989). The transfer problem is essentially due to both anatomical and geometrical constraints to the system.

Most joints allow rotations to occur which means that translations of the body's CoG, translations of a ball accelerated by the hand, or more specifically translations of a baseball bat by the hands, are predominantly a result of the transformation of rotations in joints into these translations (VanIngen Schenau, 1989). Especially in ballistic movements where the body CoG (or a ball etc.) is to be accelerated from a low or zero velocity to a velocity as high as

possible, (VanIngen Schenau, 1989) which is the main goal of baseball hitting, this transformation is inhibited by constraints. VanIngen Schenau, (1989) and VanIngen Schenau, Bobbert, & Rozendal, (1987) classified two constraints which act on the body during the vertical jump as: anatomical and geometrical. It was debated that when performing a vertical jump it is impossible to maintain a positive acceleration of the velocity difference of the hip and ankle (V_{HA}) up to full extension (VanIngen Schenau, Bobbert, & Rozendal, 1987). If the knee approaches full extension, V_{HA} will fall to zero independently of the knee extension velocity and the hip can then no longer be removed from the ankle. The transformation of the knee angular velocity into the translational velocity difference V_{HA} is less effective the larger the knee angle (VanIngen Schenau, Bobbert, & Rozendal, 1987) which exploits the geometrical constraint. Moreover, the anatomical constraint is exploited to prevent hyperextension of the knee joint with knee angular velocity decelerated to zero to prevent injury to the joint.

The results revealed that peak velocity difference between the hip and ankle (V_{HA}) is reached at a mean knee angle of 132° . At the instant of the 132° angle, rapid planter flexion is initiated and reinforced by a strong surge of activation of the gastrocnemius (VanIngen Schenau, Bobbert, & Rozendal, 1987). The authors suggested that the bi-articular nature of the gastrocnemius muscle allows the knee

extensor muscles to continue to deliver work produced at the muscle and then transport the work to the ankle joint where it is utilized for plantar flexion of the ankle joint (VanIngen Schenau, Bobbert, & Rozendal, 1987). The authors concluded that the optimal capabilities of the muscles located more proximal on the body would not be possible without the use of bi-articular muscles or by merely possessing mono-articular muscles.

Furthermore, a temporally ordered sequence in increase of muscular activity while performing a jumping motion seems to be associated with the aforementioned proximal-to-distal sequence of joint rotations necessary to eliminate a premature termination of the push-off phase (VanIngen Schenau, 1989). The power produced at the mono-articular muscles appeared to be transported to joints where it can continue to contribute usable energy to the performer. Coactivation was also observed in the mono-articular agonist muscles and bi-articular antagonist muscles which are vital in transporting the work produced from one joint to another (VanIngen Schenau, 1989). The coordination of the muscles is also an important facet because it affords an effective utilization of the work capacity of the muscles to increase the effective energy on the jumper without a loss of mechanical energy (due to heat dissipation) in eccentric contractions (VanIngen Schenau, 1989). The use of bi-articular muscles (minimum

number of three segments per extremity) have been observed in all running and jumping animals. The mass distribution over the segments and within the distal segment and the long tendons appear to be highly functional elements needed to solve the problems associated with anatomical and geometrical constraints in the transfer of joint rotations to translations (VanIngen Schenau, 1989).

In agreement with the work of VanIngen Schenau (1989) and VanIngen Schenau, Bobbert, & Rozendal (1987), Gregoire, Veeger, Huijing, and VanIngen Schenau, (1984) conducted an experiment to test the hypothesis of a proximal-to-distal energy flow from the gluteus maximus through the rectus femoris and gastrocnemius to the ankle joint during the sequential extension of the hips, knees and ankles during a countermovement jump. Eight healthy participants performed three maximal, two-legged countermovement jumps with their upper extremities positioned akimbo. Kinematics were collected via a 16mm film sampling at 100 frames per second, kinetic data were collected via a Kistler force platform and muscular activity was collected via EMG. The results of this study showed that in the second part of the push off phase, there was a high power output of ~3,000-4,000W which was delivered to the ankle joint during plantar flexion (VanIngen Schenau, 1989).

Coordinated actions of the gluteus maximus and rectus femoris along with the knee extensors and the gastrocnemius, power produced by the mono-articular extensors of both the hip and knee joints were transported distally via the bi-articular muscles to the ankle joint for plantar flexion (Gregoire et al., 1984). At the end of the push-off phase, a high plantar flexion velocity was observed as the last link in the 'chain' terminated contact with the ground. As a consequence of the high plantar flexion velocity, hip and knee extension velocity was also high which would result in relatively low contraction velocities of the bi-articular muscles (VanIngen Schenau, 1989). A low contraction velocity of the bi-articular muscles affords the muscle to produce a greater level of force allowing the transport of energy in a proximal-to-distal fashion. This sequential movement also affords the muscle to decelerate the angular velocity at the hip and knee joint and transfers the rotational energy of the upper and lower legs (Gregoire et al., 1984) into translational energy without losses in energy due to eccentric contractions.

Many evaluations of segmental sequencing in jumping, throwing or striking movements have specified a proximal-to-distal sequencing and the use of mono- and bi-articular muscles in maximizing end-point velocities and angular velocities of a specific joint. However, there is a paucity of information dealing with long-axis rotations and how they

relate to this proximal-to-distal sequencing. Relatively recent, Marshall and Elliott (2000) investigated the utilization of long axis rotation, which the authors think is the missing link to proximal-to-distal sequencing. Marshall and Elliott (2000) state that during movements such as kicking a stationary ball (commonly utilized in soccer) neither segmental long axis rotation contribute significantly to the speed of the foot, while such movements as throwing a baseball or a forehand drive in squash are only effective if the skill takes advantage of movements about all three axes of rotation. Furthermore, an aspect of these skills is that the potential for rotation about each arm segment's long axis is exploited so that maximum speed is generated at the end of the kinematic chain (Marshall & Elliott, 2000).

Elliott, Marshall, and Noffal (1995) studied eleven male tennis players performing a high-speed tennis serve while Elliott, Marshall and Noffal (1996) studied eight male and female squash players performing a forehand drive. For the tennis serve, results indicated major contributions to the mean linear velocity of the center of the racquet head of 31 meters/second at impact were: internal rotation of the upper arm (54.2%), flexion of the wrist (30.6%), horizontal flexion and abduction of the upper arm (12.9%), and racquet shoulder linear velocity (9.7%) (Elliott, Marshall, & Noffal, 1995; Marshall & Elliott, 2000). A graphical representation of the movement during the tennis

serve was illustrated which clearly showed a sequence of rotations with the upper arm flexion and abduction peaking first, followed by elbow extension, wrist ulnar flexion, wrist flexion and upper arm internal rotation and finally pronation (Elliott, Marshall, & Noffal 1995); Marshall & Elliott, 2000). Although the linear velocity of the end-point for each segment specifies a proximal-to-distal pattern, the angular velocity showed that long-axis rotations to be the final movements contained within to the sequence, which is a significant addition to the proximal-to-distal configuration of movement.

Elliott, Marshall and Noffal (1996) examined the influence that segment rotations of the upper limb assist to the mean racquet head velocity of 30.8 meters/second in the squash forehand drive. Results revealed that internal rotation of the upper arm again made the largest contribution for forward velocity (46.1%), followed by wrist flexion (18.2%) and forearm pronation (12%). Much like Elliott, Marshall, & Noffal (1995), a graphical representation was of the movement during the squash forehand was illustrated which clearly showed segmental angular velocities similar to that of the tennis serve, with upper arm flexion and adduction peaking first, followed by wrist ulnar flexion and elbow extension with pronation, wrist flexion and upper arm internal rotation reaching maximum velocity immediately prior to impact (Elliott, Marshall and Noffal, 1996; Marshall & Elliott, 2000). Both of these

studies provided information on the mechanisms of fast racquet strokes and confirm the significance of long-axis rotations to exploit maximal end-point velocities when dynamically wielding an implement.

More recently, Hirashima, Yamane, Nakamura, and Ohtsuki, (2008) investigated how baseball players generate large angular velocity at each joint by coordinating the joint torque and velocity dependent torque during overarm throwing. For the reader, it is important to define velocity dependent torque. Angular accelerations are produced not only by the muscle and gravity torques, but also by velocity-dependent torques. When velocity-dependent torque is prominent during a movement, it is difficult to determine the contribution of a muscle force to the system behavior (Hirashima et al., 2008). Muscle force at a certain instant not only produces instantaneous accelerations on the system but also influences accelerations of the subsequent system through the velocity-dependent torque because the instantaneous accelerations accumulate in the system as velocity (Hirashima et al., 2008). Therefore, muscle-induced accelerations includes only the instantaneous effects from the muscle force at that instant, while in contrast, the accelerations induced by the velocity-dependent torque reflects the cumulative effects from all history of all muscles and gravity torques *until* that instant (Hirashima et al., 2008). It is the effect of the

velocity-dependent torque on a joint angular acceleration that is related to the 'whip like action' and proximal-to-distal sequencing because angular accelerations in a multi-joint system, such as baseball pitching or hitting, must be determined simultaneously (Hirashima & Ohtsuki, 2008).

Hirashima et al., (2008) analyzed the pitching motions of six right-handed baseball players while they were instructed to throw straight balls aiming at a target under three conditions: slow accurate, medium accurate, and fast accurate while a 3-D motion analysis system tracked 11 retro-reflective markers at 200Hz. Results for the trunk indicated the initial forward acceleration was mainly made by the forward force at the trunk and the leftward angular acceleration was produced by leftward rotation torque at the trunk which was counteracted by the shoulder horizontal flexion torque, while the velocity dependent torque made little contribution to the acceleration of transitional and angular motions (Hirashima et al., 2008). Results from the shoulder indicated that there was an external rotation up to ~-30 milliseconds where the angular velocity of internal rotation increased as the time to ball release approached (Hirashima et al., 2008), although usually peaking just after ball release. The velocity dependent torque decelerated the internal rotation up to ~-10 milliseconds (Hirashima et al., 2008); it accelerated internal rotation around ball

release. The horizontal flexion torque at the shoulder joint, along with the leftward torque at the trunk, counteracted each other due to low angular velocity and acceleration of shoulder horizontal flexion in comparison with those of shoulder internal rotation (Hirashima et al., 2008).

Results at the elbow joint indicated that the elbow was initially flexed ~-130 milliseconds and then extended as the time of ball release approached with extension acceleration produced mainly by velocity-dependent torque. Initial acceleration of elbow extension was produced by elbow joint torque around -100 to -50 milliseconds in some subjects, the elbow joint torque decelerated elbow extension during -20 milliseconds prior to ball release in all subjects (Hirashima et al., 2008). Finally, results at the wrist indicated that it was initially extended at ~-50 milliseconds then subsequently flexed as ball release drew near. This observed wrist flexion was produced by velocity-dependent torque, horizontal flexion torque at the shoulder joint, elbow flexion torque and wrist flexion torque with a strong counteraction by internal rotation torque at the shoulder joint and wrist extension torque (Hirashima et al., 2008).

Across all subjects, the proximal trunk and shoulder joint motions were accelerated by the specific joint forces and torques, while the distal elbow and wrist motions were accelerated by the

velocity-dependent torque (Hirashima et al., 2008). The results from this study showed that angular velocities of the trunk and upper arm produced a velocity-dependent torque which was utilized for initial elbow extension acceleration which, in turn, increased elbow joint angular velocity and subsequently forearm angular velocity (Hirashima et al., 2008). The forearm angular velocity then accelerated the elbow extension, wrist flexion and accelerated the shoulder internal rotation during a finite period around ball release. This sequence utilized by the participants suggests that baseball players, while throwing, accelerate the distal segment (elbow and wrist) rotations by exploiting velocity-dependent torques which is produced first by the proximal (trunk and shoulder) joint torques in the early stages of throwing (Hirashima et al., 2008).

2.2 Swing Trajectory

In 'The Physics of Baseball,' Adair (2002) summarized the importance of pitching, running, fielding, and hitting. This book described a biomechanical model of the swing, collision between the baseball and bat, and specifics of the environment which could alter both the ball post impact and the effects of the swing and ball flight. He also stated that a hitter with extensive experience tends to make contact with the incoming pitch with a specific section of the baseball bat called 'the sweet spot' (Adair, 2002). The term 'sweet spot' is

remarkably difficult to precisely define due to the fact that there is a large amount of controversy to its location; therefore various identifications were constructed to explain this location on that bat. Various terminology for the 'sweet spot' are as follows: 1) center of percussion, 2) the maximum energy transfer point, 3) the maximum batted-ball speed point, 4) the maximum coefficient of restitution point, 5) the node of the fundamental vibration mode, 6) the minimum sensation point, and 7) the joy spot (Bahill, 2004). Due to the fact that Bahill (2004) found that after the author measured a large number of bats and found that the sweet spot was about 80 to 85% of the distance from the knob to the end of the bat. For ease, and the large consistency of this location by Bahill (2004), a single definition will be used to specify this location which is: 'When the ball hits the bat, it produces a translation that pushes the hands back and a rotation that pulls the hands forward; when a baseball is hit at the center of percussion (CoP) for the pivot point, these two movements cancel out, and the batter feels no 'sting'' (Bahill, 2004).

When speaking about this location of the baseball bat, it assumes that the baseball is perfectly struck, which in a real life scenario happens less frequent than striking a baseball imperfectly. There are minimal differences in the location of where the ball is struck which have massive implications as to where the ball will be located

post impact. Fortenbaugh, (2011) nicely summarized this point stating that when 'assuming a ball is hit solidly to centerfield for a base hit with a level swing, swinging the bat 50 millimeters below the ball's center will result in a ball fouled high and straight back over the catcher's head and out of play, swinging the bat 25 millimeters below the ball will be a routine fly-out, but swinging the bat 19 millimeters below the ball's center will maximize the ball's flight distance, partially by creating backspin to further propel the ball.'

Fortenbaugh, (2011) further stated that 'it is suggested that an effective ground ball hit should not make contact more than 10 millimeters above the ball's center.' In regards to a standard 30 inch length bat, the 'sweet spot' will be located anywhere from 24-25.5 inches (80-85% of the length of the bat) from the knob end, which most effective hitters claim to have the most success when striking the ball at this location. However, with extremely small variances in the location of the sweet spot and where ball contact actually takes place, one can see that, with a ball that is struck away from the sweet spot or at different locations of the ball, negative implications on the hitting outcome are observed.

It is apparent that, from the summary by Fortenbaugh, (2011) stated above, situations where two objects impact each other are extremely difficult to control with baseball hitting acting as a perfect

example of such an impact. To fine tune the skills needed to successfully make contact with another object, baseball hitters frequently perform 'dry swings' where the hitter performs the hitting motion without the presence of an object to impact which give the hitter an advantage of imagining hitting the incoming pitch, the swing motion and situational awareness (hit and run). However, the 'dry swing' inherently possesses a distinct disadvantage of the knowledge of results not being readily available from swing to swing. Hence the reasons why batting simulators were adopted for baseball hitters to encompass the advantages and disadvantages of the 'dry swing' to further understand the characteristics, such as trajectory and peak velocity, of the swing around the time of bat-ball contact.

Tabuchi, Matsuo, and Hashizume (2007) investigated bat speed, trajectory and timing for collegiate baseball batters hitting a stationary ball. Eight male (6 right-handed hitters and 2 left-handed hitters) volunteered to participate to hit three balls of different weight, ten times each, in three conditions: 1) normal baseball of standard weight (diameter - 73 millimeters, mass -150g), 2) polystyrene ball (diameter - 70millimeters, mass- 8.0 g) and 3) small polystyrene ball (diameter - 15 millimeters, mass - 0.2 g). The experiment consisted of six blocks of five trials that included two sets with each type of ball. The order of blocks was randomized and counterbalanced with the

participants. Each participant was requested to hit a line drive towards a net which was located 3 meters away from the participant as a target (Tabuchi, Matsuo, and Hashizume, 2007) while four infrared cameras sampling at 240Hz were used to capture the reflective markers on the hitter and the ball.

Furthermore, an additional experiment was conducted to investigate the bat kinematics of hitting a stationary ball compared to hitting a moving target. Four left-handed collegiate hitters participated in this auxiliary experiment, but did not participate in the main study. They were instructed to hit a ball under two conditions: A) to hit a small polystyrene ball, which was hung with a string (same as Condition 3 of the main experiment) and B) to hit a pitched plastic ball. In Condition B, each participant was asked to hit a plastic ball (diameter - 70mm; mass- 50 g) 100 times thrown at about 20 meters/second from a distance of 12 meters (Tabuchi, Matsuo, and Hashizume, 2007) while three-dimensional locations of the bat and the ball markers were documented by the same method as in the main experiment.

Results for the auxiliary experiment showed that the kinematics of the bat head in Condition B were not significantly different from those in Condition A, when the impact points were close together (Tabuchi, Matsuo, and Hashizume, 2007) however, trajectories of the bat head under Condition A and B in the horizontal plane and those in

the sagittal plane showed significant cross-correlation coefficients. Additionally, speeds of the bat head immediately before impact were not significantly different (32.2 ± 0.9 m/s under Condition A and 32.7 ± 1.8 m/s under Condition B) (Tabuchi, Matsuo, and Hashizume, 2007). The results for the auxiliary study lead the authors to conclude that the bat kinematics of hitting a stationary ball were not significantly different from those of hitting a moving ball (Tabuchi, Matsuo, and Hashizume, 2007).

Results for time for peak speed of the bat head for the main study showed mean times for the peak speed of the bat head under Conditions 1, 2, and 3 were 20.2 ± 0.4 milliseconds, 10.1 ± 8.5 milliseconds, and 12.0 ± 7.4 milliseconds, respectively. A Tukey's post-hoc test was used to show where the difference occurred, which revealed that time for peak speed in Condition 1 was significantly earlier than that in Condition 2 and that in Condition 3. Bat head speed, for the majority of participants, reached peak speed post impact when balls of a lighter mass was struck while for Condition 1, peak speed was very close to impact when a standard weight ball was utilized (Tabuchi, Matsuo, and Hashizume, 2007).

For 75% of the participants under Condition 1, the peak speed of the head of the bat consistently occurred at impact. Results for time for the lowest position of the bat head showed mean times for the

lowest position of the bat head under Conditions 1, 2, and 3 were 3.6 ± 6.6 milliseconds, 3.5 ± 6.6 milliseconds, and 3.5 ± 6.0 milliseconds, respectively. For most participants, the time for the lowest position was within 8.3 milliseconds of impact with the ball for each condition (Tabuchi, Matsuo, and Hashizume, 2007). Lastly, results for peak speed of the bat head showed mean peak speeds of the bat head under Conditions 1, 2, and 3 were 33.4 ± 0.9 meters/second, 33.6 ± 0.8 meters/second, and 33.4 ± 1.0 meters/second, respectively. The peak speed of the bat head for all participants was not significantly different among conditions.

Throughout the conditions, peak speed of the head of the bat varied accordingly. Condition 1 showed bat head peak speed occurring at the instant of impact, while when the less massive balls were used, peak speed was observed in a range of 5-17 milliseconds post impact (Tabuchi, Matsuo, and Hashizume, 2007). Peak speed at impact in Condition 1 resulted from the large impulse of the impact and that the speed would have continued to increase if impact had not occurred (Tabuchi, Matsuo, and Hashizume, 2007). Hitters did not hit the lightweight balls when the bat was at peak speed or in the deceleration phase, rather the impact occurred in the acceleration phase prior to maximum speed (Tabuchi, Matsuo, and Hashizume, 2007). Peak speed of the bat head, as measured in Condition 1, was an outcome of

the large impulse produced by the impact. If the impulse was small enough, the peak speeds occurred at about 17ms after the impact. Thus, the bat–ball impact occurred as the speed of the bat head was increasing (Tabuchi, Matsuo, and Hashizume, 2007) which is in accordance with McIntyre and Pfautsch, (1982), Messier and Owen (1984), and Welch et al., (1995) who found peak speed of the bat head in a time other than at impact.

McIntyre and Pfautsch, (1982), required twenty current or former college baseball players to hit a pitched baseball into two assigned areas of the field and demonstrated that peak speed of the bat head was reached 13–16ms before impact. These results indicate that the bat struck the ball at sub-maximum speed and that the impact occurred in a deceleration phase after peak speed (McIntyre and Pfautsch, 1982; Tabuchi, Matsuo, and Hashizume, 2007). Messier and Owen (1984) instructed eight intercollegiate softball players to hit a pitched softball and demonstrated that the bat head reached a maximum speed 32 milliseconds before impact (Messier and Owen 1984; Tabuchi, Matsuo, and Hashizume, 2007). Welch et al., (1995) examined bat kinematics during tee batting. In their study, 29 male professional baseball players hit balls on a batting tee. The authors found that the maximum speed of the bat head occurred 15

milliseconds before impact with the ball (Welch et al., 1995; Tabuchi, Matsuo, and Hashizume, 2007).

Results from the main study conducted by Tabuchi and colleagues (2007) showed that the minimum height of the bat head could be used as an approximation for the point of impact, which again supports Welch et al., (1995) who found that the bat had negative vertical velocity (downward movement) prior to impact. The velocity then proceeded to 0 meters/second at the instant of impact, which was followed by a positive vertical velocity (upward movement) post impact. This suggests that impact occurred around the time where the bat head was at the deepest point during the swing (Tabuchi, Matsuo, and Hashizume, 2007).

To gain an advantage, a hitter should attempt to impact the ball at the instant of peak bat head speed, which was not observed in this study. Making contact while the bat head is still accelerating may have benefits such as spatial accuracy. The spatial margin of error for impact requires accuracy, in the vertical direction, of ± 12.7 millimeters (Watts and Bahill, 2000; Tabuchi, Matsuo, and Hashizume, 2007). Vertical displacement of the head of the bat in a finite time period is minimized around the deepest point of trajectory, which means small temporal errors do not result in large spatial errors around the lowest position of the bat; in fact, the participants swung the bat head to its

lowest point in the trajectory within an average of ± 7.8 milliseconds from impact with the ball. (Tabuchi, Matsuo, and Hashizume, 2007). In conclusion, regardless of conditions, the timing of the lowest point of the bat head was nearly identical for each batter and most participants hit the stationary balls at about the lowest point of the bat trajectory (Tabuchi, Matsuo, and Hashizume, 2007). The task in this study was to contact a stationary target; rationally it makes sense to make contact with the ball at the time where the bat head reaches its deepest point.

In a study done by Sawicki, Hubbard and Stronge, (2003) focused on optimal bat swing parameters for maximum range trajectories. The authors expanded on Adair (2002) work which stated that if one were to improve the swing parameters, the distance the hit ball travels would also be improved. The authors obtained results with regards to the Magnus effect, optimal Reynolds number, drag forces, increased pitched ball speed and bat velocity.

Results for the swing parameters stated that for optimal post contact batted-ball distance, the hitter should employ a swing strategy with specific values of a 9° undercut swing angle .0265 meters (27 millimeters) below the midline (horizontal axis) of the ball when hitting a fastball (Sawicki, Hubbard and Stronge, 2003). This strategy proposes that hitters should match the angle of the swing with that of a pitched ball to hit a home run. Therefore, if hitters want to maximize the

range of the ball post impact, the impact should transpire around the time of the peak speed of the bat head, which will deliver a higher speed of the bat head and an increased probability of successfully hitting the pitch (Tabuchi, Matsuo, and Hashizume, 2007). It was observed that the distance of the hit ball was most sensitive to bat velocity, which suggests that a hitter should work to enhance bat velocity before concentrating on anything else to increase the distance of their hits.

2.3 Effects of Various Weighted Devices on Bat Velocity

Fundamental to playing successful, offensive baseball, is to make contact with the ball with enough force to effectively reach base safely. The most effective way to do so is to hit the ball over the outfield fence and out of the playing field, giving the defensive players zero chance of recording an out via a groundball or pop fly to one of the fielders. To complete this accomplishment, the batted ball must travel a minimum of one-hundred meters (Pillmeier, Litzemberger, & Sabo, 2012). A key parameter to achieve this distance is the speed in which the ball is hit and leaves the bat. The speed at which the ball leaves the bat is influenced by the hitter's swing mechanics and muscular strength (Szymanski et al., 2010a). Therefore, hitters strive to increase bat velocity. Traditionally, hitters use weighted bats for a warm-up prior to swinging a standard game bat during a live game situation. In today's

game, the weighted device added to the athletes bat can vary greatly from a 16oz 'donut' ring and a 24oz 'Pow'r wrap, which are added to the standard bat,' to a 96oz Schutt Dirx adjustable warm-up bat with the idea of increasing post warm-up bat velocity to impart a larger amount of necessary energy to the batted ball.

In a study done by Montoya et al., (2009), nine-teen recreational male baseball players were randomly assigned to one of three conditions: light bat (9.6oz), normal bat (31.5oz), or heavy bat (55.2oz). Each subject then completed 5 maximal warm-up swings with each of the three different bats on three different days. After the warm-up swings were completed, they rested for thirty seconds and then completed five maximal swings with a normal bat. Results obtained from breaking the beam of two vertical photoelectric sensors positioned the depth of home plate (45cm) showed warm-up velocity of the light bat was significantly faster than that of the normal bat and the heavy bat; whereas warm-up velocity of the normal bat was also significantly faster than that of the heavy bat (Montoya et al., 2009).

Given that post warm-up velocity of the light and normal bat condition produced significantly greater velocity than the heavy bat condition it was concluded that the use of warm-up swings with a heavy donut attached to the bat should be discouraged because it appears to reduce speed when returning to the normal bat (Montoya et

al., 2009). Based upon the findings of this study the authors further suggested that five warm-up swings with either a very light bat (~10oz) or a normal bat (~31oz) will allow a player to achieve maximum velocity of their normal bat (Montoya et al., 2009).

Montoya et al., (2009) employed two physical bats (light and normal) and used a donut attached to the normal bat which made up the heavy bat condition, therefore making them the same with regard to length, with the only variation in weight of the implement which is very similar to what DeRenne, Ho, Hetzler, & Chai, (1992) used. Conditions in this experiment were very practical to the real on-deck circle situation being that it is common practice among most baseball athletes to place the donut on the standard bat to warm-up the muscles used during the swing, prior to stepping up to the plate to face real pitching (Montoya et al., 2009).

Findings from Montoya et al., (2009) are somewhat consistent with the findings from DeRenne, Ho, Hetzler, & Chai, (1992). This study used sixty male varsity high school players using a wide variety of implements which included: five over weight bats weighing 51, 48, 45, and 34ozs; one 30oz standard weight bat; four under-weighted bats at 29, 27, and 23ozs; one standard weight bat with a 28oz donut (total weight 58oz); a 4oz Power sleeve (total weight 34oz) and a Power Swing (total weight 62oz). All bats were aluminum with identical

lengths and shapes. The additional weight on the heavier bats was added to the distal end of the barrel, while the under-weight bats were shaved off by machine work throughout the entire bat (DeRenne, Ho, Hetzler, & Chai, (1992).

Results obtained showed no significant differences in bat velocity between three swings while using the same warm-up implement. However, significant differences were found in bat velocity as a result of using various warm-up implements. Warm-ups using a bat within 27-34oz range produce the greatest bat velocity when swinging a standard bat (DeRenne, Ho, Hetzler, & Chai, 1992). Among the devices, a very light (23oz), very heavy bat (51oz), and the standard bat with a donut (58oz) produced the slowest bat velocities. It was concluded that swinging a very light or over-weight bat immediately prior to hitting with a standard bat may have a negative impact on bat velocity and that use of a donut ring, which is widely used in all levels of play, consistently produced the slowest bat velocities (DeRenne, Ho, Hetzler, & Chai, 1992).

Conditions for the study conducted by DeRenne, Ho, Hetzler, & Chai (1992) consisted of greater extremes in the amount of swings and weight of the bat which may explain slightly different results. Montoya et al., (2009) found that a bat as light as 9.6oz produced the same amount of velocity as a normal bat of 30oz and that both produced

more velocity than the heavy bat. The heaviest bat used by DeRenne, Ho, Hetzler, & Chai (1992) was 62oz and the lightest bat was 23oz, with each producing the slowest normal bat velocities. However, the warm-up condition was 4 swings followed by 2 swings of a normal bat compared with DeRenne, Ho, Hetzler, & Chai (1992) warm-up condition with 5 swings followed by 5 swings with a normal bat. Also, there were differences between the sample populations utilized by both studies. Most studies utilized highly skilled and trained collegiate baseball players who regularly engage in practice sessions and game situations, whereas Montoya et al., (2009) used recreational players who may only play on the weekends, while DeRenne, Ho, Hetzler, & Chai, (1992) studied high school athletes.

Southard and Groomer (2003) findings with ten experienced baseball players (six active members on the University baseball team and four having at least varsity baseball experience in high school) further support the findings of Montoya et al., (2009) and DeRenne, Ho, Hetzler, & Chai, (1992). This study utilized three different bats 1) 'standard' bat (34oz), 2) 'weighted' bat (standard bat with a 22oz donut) and 3) 'light' bat was a plastic hollow bat (12oz). Participants were randomly assigned until all participants performed swings in each condition followed by swings with a standard bat.

Results showed significant difference by condition where the weighted bat condition was significantly less than the standard bat and light bat conditions (Southard and Groomer, 2003). The study concluded that it is advantageous for the hitter to use the bat they expect to use during the game because, when interpreting the results from a dynamical systems perspective, the bat is an extension of the performer because pattern change is a function of the interactions among the constraints from the individual, environment, and task (Southard and Groomer, 2003). Using a bat with a larger moment of inertia not only slowed the swing, but altered the swing pattern and required a reorganization of the hitters motor program used when hitting with a standard bat (Southard and Groomer, 2003).

While one might expect that Southard and Groomer (2003), Montoya et al., (2009) and DeRenne, Ho, Hetzler, & Chai, (1992) would obtain similar results given that these studies used extreme bat weights ranging from 56oz in the heavy condition to 12oz in the light condition; 55.2oz in the heavy condition to 9.2oz in the light condition; and 62oz in the heavy condition to 23oz in the light condition, respectively the findings were not consistent with respect to the population utilized as stated above. Differences in the study populations (experience, physical maturity etc.) tested in these studies could have impacted the findings.

Specifically, Montoya et al. (2009) study population of recreational athletes were less trained and possibly less efficient in recalibrating the motor system to the device in hand during an in game situation after dynamic wielding of an altered (weighted) bat than the collegiate athletes in Reyes and Dolny (2009) study. This difference could have resulted in a greater post warm-up effect as a result of being less trained subjects used by Montoya et al. (2009), DeRenne, Ho, Hetzler, & Chai, (1992) and the four participants that were not playing at the collegiate level in the work done by Southard and Groomer (2003).

In contrast to the previous studies, Reyes and Dolny (2009) recruited nineteen subjects from a National Collegiate Athletic Association Division III collegiate baseball team where three conditions were used to assess the influence of bat weight on hitting performance. An aluminum bat, defined as the 'standard' bat (30oz), a second aluminum bat defined as the 'light' bat (28oz), and a 'heavy' bat (54oz), (combination of the 'standard' bat (30oz) and the Pow'r Wrap (24oz)) were the three conditions used. Results revealed that all weighted bat warm-up protocols improved bat velocity compared to control; however, the improvements did not reach statistical significance.

Although not significant, the results indicate that an improvement did exist which cannot go unrecognized (Reyes and Dolny, 2009). The use of the weighted bat appeared to have a positive effect on post warm-up bat velocity, whereas the previous studies showed the contrary. With any increase in post-warm bat velocity, it increases the distance the ball travels. Adair, (1990) work which revealed, that there is a positive relationship of bat velocity and the distance the ball travels after impact further supports these findings. Therefore, even with insignificant findings of increased bat velocity, the small positive affect the results revealed may increase the chances of a successful at bat and reaching base safely because of the increased velocity of the batted ball. With a large effect size of .803 and power computations revealing a .99 score (Reyes and Dolny, 2009) although results were not significant, this suggests that the results are meaningful and have useful effects when applied to practical competitive situation.

Baker, (2001) reported that when attempting to increase power with a lighter weight, it is best to warm up in a descending order of resistance, with the final weight being the one you anticipate to use during competition. The heavy warm-up load stimulates the neural system, allowing for increased muscle activation during the standard bat swings (Baker, 2001). Therefore, protocols ending with the

standard bat would have produced a greater bat velocity, especially protocol two (heavy bat, light bat, standard bat), where the order of the weighted bats was in descending order (Reyes and Dolny, 2009). Utilizing the specific order of descending weight of heavy, light, then standard elicited the 3rd highest ranked increase in bat velocity (Reyes and Dolny, 2009).

Enhancing bat velocity increases the balls exit velocity off of the bat which increases the distance the batted ball travels, thus improving performance. According to previous researchers (Adair, 2002; Hay, 1985) and current and past coaches, one specific way in which a baseball hitter can increase their potential for success is to increase their bat swing velocity. Three benefits of increased bat swing velocity are increased decision time, decreased swing time (Hay, 1985; Hetzler, DeRenne, Buxton, & Ho, 1997), and increased batted-ball velocity (Hetzler, DeRenne, Buxton, & Ho, 1997).

Hitting a baseball is arguably the most difficult task to achieve in sports. The ability to make contact with an object that is 7.62 centimeters in diameter with an implement measuring 6.98 centimeters in diameter requires extremely accurate and specific information obtained by the hitter in a very short amount of time. If a collegiate baseball pitcher throws a 90 mile per hour fastball, it will reach home plate in 0.4 seconds (Szymanski, DeRenne & Spaniol, 2009). Within

this finite time span, hitters must quickly recognize three variables: type of pitch thrown (i.e., fastball, change-up, breaking ball), the velocity of the pitch, and the location of the pitch (Szymanski, DeRenne & Spaniol, 2009). The longer the hitter can wait before swinging (increasing decision time), the more likely it is that the hitter will swing at a ball in the strike zone (be more accurate at the point of contact) and arrive at the appropriate time, which are the two most important goals in successful hitting (Szymanski, DeRenne & Spaniol, 2009).

Therefore, Reyes and Dolny (2009) recommend weighted bat warm-up order of standard, light, heavy (protocol four) as a means to increase bat velocity, which contradicts the recommendations from Baker, (2001), because a 6% increase in bat velocity was observed. With increased bat velocity, less time is taken to swing the bat, and thus the longer the hitter has to make a decision regarding batting. Thus, if a hitter could decrease the swing time, they would have an extended decision time, which would allow the hitter to be more selective in the batter's box (Szymanski, DeRenne & Spaniol, 2009). This would directly affect the hitter's ability to identify the three aforementioned variables, which would increase the possibility of being more accurate to contact the ball and reach base safely.

Szymanski et al., (2011) utilized twenty-two intercollegiate Division-I baseball players subjected to ten different devices to use as a warm-up in attempt to further exemplify this notion. The specific devices used in this study were a 'standard' aluminum baseball bat (30oz). seven overweight: Pitcher's Nightmare Swing Trainer (resistance band attached to back leg and arm while swinging standard bat), 96oz Schutt Dirx adjustable warm up bat, weighted batting gloves (50oz) while swinging a standard bat, Pow'r Wrap added to standard bat (54oz), 16oz donut ring added to standard bat (46oz total), 14oz power fins air resisted device added to standard bat (44oz total), 34oz wooden bat, 2 underweight devices: 26oz bat aluminum bat and 22oz aluminum fungo bat.

Interestingly, the results revealed no overall significant difference between the mean bat velocities after swinging any of the ten warm up devices. Yet the findings of DeRenne, Ho, Hetzler, and Chai, (1992) which used a similar range of implements did find statistically different results. This discrepancy could be attributed to the level of play, or experience in which the sample population that DeRenne et al. (1992) tested. Being that high school athletes were tested, the results could be argued that the physical maturity is not quite at the high level of a collegiate athlete because of the minimum of two years additional experience by the collegiate athletes (Szymanski

et al., 2011), which in turn leads to increased strength and better hitting mechanics than that of the high school population. With no significant differences, Szymanski et al., (2011) concluded that Division I intercollegiate players interested in having the highest bat velocities during a game situation using a 'standard' bat can use any of the ten implements tested because bat velocities were not statistically significant from one another.

Although this study showed no significant differences between implements, it is interesting to see that the two most commonly used warm-up devices (donut and Pow'r Wrap) produced slower bat velocity similar to previous research (DeRenne, Ho, Hetzler, & Chai, 1992; Montoya et al. 2009; Southard and Groomer 2003; Otsuju, Abe, and Kinoshita, 2002). Southard and Groomer (2003) state that the moment of inertia, which is the ease of angular motion of the bat, is the main determinant to how easy or hard it is to swing a warm-up device. Being that the donut and Pow'r Wrap are placed toward the distal end of the bat; the moment of inertia is severely affected.

Again, physical maturity and increased strength that the collegiate players possess plays a role in overcoming the inertia imparted on the implement by the distally added weight. Significant results between various warm-up devices on bat velocity of high school players revealed by DeRenne, Ho, Hetzler, & Chai, (1992) is not

applicable for the more mature, physically stronger intercollegiate players who are able to overcome the added inertia at the distal end of the implement. Therefore, Szymanski et al., (2011) recommends that baseball players follow the guidelines of DeRenne et al. (1992) and swing warm-up bats that are $\pm 10\%$ of their standard game time bat where the weight is evenly distributed.

2.4 Motor Re-Calibration to Weight Changes/Kinesthetic

Aftereffects

During a daily routine, one is required to interact with objects in the environment. In the sporting arena for example, racquets, golf clubs and baseball bats are commonly utilized to successfully engage in competition. For these implements to be used efficiently, the participant must have the capabilities to calibrate the motor system, more specifically the perceptual-motor control, to the specific properties of the specific tool being utilized. Activation of the muscles that is required to hit a baseball with a bat that weighs 30oz varies greatly from the muscular activation that is required to hit a ping pong ball with a racquet that weighs 6oz. Calibrating the motor system progresses through stages of complexity, especially when the participant is instructed to abruptly switch the specific implement in hand because these changes, in a finite period of time, can create interference which may hinder motor learning (Cothros, Kohler, Dickie,

Mirsattari, Gribble, 2006) and the consolidation of motor memories (Brashers-Krug, Shadmehr, Bizzi, 1996).

Ability to switch from one implement to another has been studied in baseball hitting. DeRenne et al. (1992) found that maximum bat velocity for a game bat of 30oz occurred when batters warmed-up with a bat that was within $\pm 10\%$ of the game bat weight. Perceived swing velocity (indicated by subjective rankings following a swing) was highest for swings following warm-up with the heaviest bats which was similar to the results described by Otsuji et al. (2002) and Southard and Groomer (2003), which will be revealed later in this section and as stated above, respectively. In a more recent study, Scott and Gray (2010) investigated changes in perceptual-motor control in response to switching tools in a task involving interaction with a moving object utilizing two separate experiments.

In experiment 1, thirty participants were assigned to one of three bat weight conditions in a hitting simulation: lighter, heavier and a control group, with bat weight variations by use of an adjustable bat weight sleeve that slid over the end of the bat barrel and was held in place with Velcro straps. During a practice session all participants used the standard weighted bat. Following the practice session, all participants completed two experimental blocks of 15 swings using the standard bat (blocks 1 & 2). Following a five minute break, the next two

blocks of trials (blocks 2 & 3) varied bat weights among the three groups where participants were randomly assigned to one of the three conditions. The control group continued used the standard bat (38oz) for Blocks 3 and 4. The Lighter group completed blocks 3 and 4 using the bat with all the weights removed resulting in a bat weight of 28oz. The heavier group completed Blocks 3 and 4 using the bat with four 5oz weights added for a total bat weight of 48oz. All participants were then given another 5-min break, followed by two final blocks (Blocks 5 and 6) using the standard bat (Scott & Gray, 2010).

Results for the four dependent variables of: mean temporal error (MTE), mean spatial error (MSE), swing onset time (SOT), and bat velocity. For MTE and MSE, it is important to note the directionality of error. A positive MTE indicates the batter swung too early (i.e., the bat crossed the front of the plate before the ball had arrived) and a negative MTE indicates the batter swung too late, while a positive MSE indicates the batter swung too high while a negative error indicates the swing was too low (Scott & Gray, 2010). Swing accuracy results indicated a significant condition x block interaction, specifically; block 3 showed significant differences in MTE between the control group and lighter group and the control group and heavier group (Scott & Gray, 2010).

To delve deeper into the results of swing accuracy, blocks 3 and 4 were subdivided into groups of five pitches (3.1 etc. and 4.1 etc.) (Scott & Gray, 2010). This analysis showed a significant main effect of condition and a significant condition x block interaction, specifically; that the difference in MTE between the lighter group and control group was significant in block 3.1 and differences in MTE between the control and heavier groups was significant in Blocks 3.1 and 3.2 (Scott & Gray, 2010). Finally, to determine whether the switch to a standard bat in block 5 had an effect, it was subdivided in a similar fashion as blocks 3 and 4. Results revealed that the difference between the control and heavier groups was significant in block 5.1 (Scott & Gray, 2010).

Results for bat speed revealed a main effect of block and a significant Condition x block interaction. Specifically in block 3, where there was a significant difference in mean bat speed for lighter versus control and for heavier versus control and in block 4, there was a significant difference in mean bat speed for heavier versus control (Scott & Gray, 2010). Blocks 3 and 4 were again subdivided into groups of five pitches. This analysis showed main effects of block and condition were significant as was the condition x block interaction. Specifically, the mean bat speed was significantly different in block 3.1 for the control versus lighter and the control versus heavier groups (Scott & Gray, 2010).

Moreover, the mean bat speed was significantly different for the heavier versus control comparisons in block 3.3 and the breakdown of interval five revealed a significant difference between the Control and lighter groups in block 5.1 (Scott & Gray, 2010). Results for swing onset time (SOT) revealed a main effect of block, specifically a significant difference between the heavier and control groups in Interval 4. A breakdown of intervals 3 and 4 revealed a significant condition x Block interaction and a significant difference between the control and heavier groups in intervals 3.2, 3.3 and 4.3 (Scott & Gray, 2010).

Furthermore, due to limitations within the first experiment, Scott & Gray (2010) conducted a secondary experiment because the weight of the bat in the heavier condition (48oz) was greater than the typical bat weight for each participant which may have led to the reason why the hitters were unable to increase bat speed, thus resulting in a decrease in temporal error of the swing (Scott & Gray, 2010). Experiment two was implemented to investigate possible alterations when switching to a heavier bat that was closer in weight to that of a typical weight that is used during a live game situation (Scott & Gray, 2010).

Twenty hitters, who did not participate in experiment 1, took part in experiment 2. This experiment was similar to that in experiment 1 with only one alteration that participants were randomly assigned to

one of two groups: control or heavier. The control group used the 28oz wooden bat with no additional weights (lighter bat from Experiment 1) for the entire experiment, while the heavier group completed Blocks 3 and 4 using the bat with four 2.5oz weights added for a total bat weight of 38oz (the control bat from experiment 1) (Scott & Gray, 2010).

Results showed a pattern of which was similar to the results found in experiment 1 (Scott & Gray, 2010) for the control and heavier groups. When the hitter switched to the heavier bat, swings were late in block 3 with the error eradicated in block 4. Specifically, in Block 3 there was a significant difference in MTE between the control group and heavier group (Scott & Gray, 2010).

Mean bat speed was slightly different than for Experiment 1. Consistent with Experiment 1, hitters in the heavier group in Experiment 2, block 3, showed significantly lower mean bat velocity. However, there were no significant differences for bat velocity between the control and heavier groups in block 4, which is dissimilar from the results from Experiment 1 and the variability of bat velocity in block 4 was much more than that showed in any facet of Experiment 1 (Scott & Gray, 2010). This variability suggests that there were individual differences in the recalibration process following the bat weight change (Scott & Gray, 2010). Further analysis was performed to investigate block 2 (standard bat) compared with block 4 (heavier bat). These data

suggest for bat speed, six of the batters had a relatively small difference in bat speed between Blocks 2 and 4 suggesting that they re-calibrated by increasing speed to that used for the standard bat (Scott & Gray, 2010). Conversely, four of the batters had a relatively large difference in bat speed between these two blocks suggesting that they did not re-calibrate by increasing bat speed (Scott & Gray, 2010).

Results for mean SOT, which were slightly different than in Experiment 1, revealed that the variability was higher for the heavier group in Block 4 than for any of the other Conditions in Experiment 2, which is similar to that of the results for bat speed (Scott & Gray, 2010). Six participants had a relatively small difference between Blocks 2 and 4 while the onset time difference for the remaining four participants was larger. This larger effect for the last four participants combined with the bat speed results suggests that these four participants re-calibrated by swinging earlier (Scott & Gray, 2010).

Experiment 1 examined the ability of hitters to switch tools in a task involving intercepting a moving object: switching between bats of different weights in baseball. Results indicated, by switching tools (bats), that when switching to a lighter and heavier bat decreased temporal accuracy of the swing which is shown by the first block of trials after the switch (Scott & Gray, 2010). Hitters who swung the light bat tended to swing too early while hitters who swung the heavier bat

tended to swing late, which can have negative implications given the finite margin of error for speed is ~ 15-20 milliseconds (Watts & Bahill 1991; Scott & Gray, 2010), however, error that was produced by the weight change had no effect on spatial accuracy of the swing, but only a timing error (Scott & Gray, 2010).

Although, there was a large effect from changing bat weights on temporal accuracy, it lasted only during a short period of time. As stated, there were no significant differences in MTE between the three groups in Block 4. Following the subdivision for blocks three and four, significant differences were observed between the control and lighter group, but only in block 3.1 (Scott & Gray, 2010). This significance may suggest that within five pitches, the lighter group adapted to the bat weight change within five pitches where when the control and heavier group were compared significant differences in blocks 3.1 and 3.2 was observed which suggests that the heavier group adapted to the bat weight change within ten pitches (Scott & Gray, 2010). In Block 3, mean bat velocity was significantly higher after the bat weight change to the lighter bat, specifically, bat velocity for the lighter group was significantly differ than for that of the control group in block 3.1(bat velocity change and MTE were extremely similar) (Scott & Gray, 2010). These discoveries suggest that the hitters in the lighter group recalibrated the timing of the swing in response to a reduction in bat

weight by reducing bat velocity to a value similar to that when the standard bat was used (Scott & Gray, 2010), which seems counterintuitive because maximizing bat velocity is the ultimate goal for any baseball player to help increase their performance.

In regards to the heavier group, there was a statistically significant decrease in bat velocity when the hitter switched to the heavier bat in block 3. Different from the lighter group, hitters in the heavier group appeared to not recalibrate their swing by changing bat velocity (Scott & Gray, 2010). Instead, the hitters in the heavier group swing onset time data suggests that the Heavier group re-calibrated by changing when the swing was initiated instead of changing swing velocity (Scott & Gray, 2010). It was shown in block 4 that the hitters in the heavier group initiated the swing earlier, usually after ten pitches (block 3).

Overall, in Experiment 1 the hitters which switched from a 48oz bat to a 38oz bat averaged temporal error was roughly 3-17 times the required margin of error (Scott & Gray, 2010) of 15-20 milliseconds proposed by Watts & Bahill (1991) and when hitters switched from a 38oz to a 28oz bat, averaged temporal error was roughly 2-13 times the required margin of error (Scott & Gray, 2010). In Experiment 2, when hitters switched from a 28oz bat to a 38oz bat averaged temporal

error was roughly 2-13 times the required margin of error (Scott & Gray, 2010) which is a clear detrimental effect on batting performance.

Results from this study suggest that a re-calibration process depends upon the capabilities of the batter along with specific individualized recommended bat weight (Bahill, 2004). A recommendation of a heavier bat weight suggests the hitter is able to generate higher velocities with a heavier bat (Bahill and Freitas 1995). When a hitter in this study switched to a lighter than recommended bat weight (lighter group in Experiment 1) or was heavier but was within roughly 15–20% of their recommended weight (first six hitters in Experiment 2) re-calibration consisted of either increasing or decreasing bat velocity (Scott & Gray, 2010). Conversely, if a hitter switched to a bat that was greater than 20% of their recommended bat weight, (heavier group in Experiment 1 and remaining four participants in Experiment 2), re-calibration involved adjusting the swing onset time (Scott & Gray, 2010).

This suggests that the preferred strategy employed by the participants is to adjust bat velocity to re-calibrate the system because bat speed is more familiar to most hitters than altering swing onset time (Scott & Gray, 2010) on account of constantly performing alterations of bat speed when standing at the plate facing pitches with various speeds in a game situation. Also, the adjustment of the bat

swing happened within five swings when SOT occurred after ten pitches which may dictate that individual limitations of perceptual motor control (Scott & Gray, 2010). Moreover, re-calibrating one's swing with a heavy bat could negatively affect hitting performance by introducing timing errors for the first few pitches when switching to the lighter game bat (Scott & Gray, 2010). However, the negative effects could potentially be absent once the hitter consistently practice switching between the heavy warm-up bat and the standard bat used in a game because of a centrally memorized, or stored, calibration state (Osu et al. 2004) that could be immediately induced when using the standard game bat. If a hitter doesn't possess a calibration state for the standard game bat that can be immediately used, it is possible swing errors could occur (Scott & Gray, 2010), while if a calibration state is stored, re-calibrating during a heavy warm-up should have little to no effect on performance once the game bat is used (Scott & Gray, 2010).

Work conducted by Otsuji et al. (2002) exemplifies the notion of little to no effect on the re-calibration state when using the standard game bat after using a heavier bat. Eight university baseball and softball players participated in this study. Two photoelectric switches and a digital data recorder were used to measure bat velocity when the participants were instructed to hit a suspended ball, hanging from a string, from the ceiling. Three sets of 15 hits were performed by each

participant with 10 minutes rest between each set. The control condition consisted of the participant hitting the ball five times using the bat without the bat ring.

Following the control condition, the weighted condition consisted of an added donut to the bat, and the ball was hit five times. Following the weighted condition, the post-weighted condition consisted of five hits without the donut. Furthermore, after the fifth swing in the weighted condition and the first, third and fifth swings for the post-weighted condition a subjective judgment of the heaviness of the bat during the swing and the speed of the swing itself compared with the control condition (Otsuji et al., 2002). A 5-point Likert scale was used for each judgment: apparently lighter (5), slightly lighter (4), equal (3), slightly heavier (2), and apparently heavier (1) for the bat weight, and apparently faster (5), slightly faster (4), equal (3), slightly slower (2), and apparently slower (1) than the Control condition (Otsuji et al., 2002).

Results for the effects of weighting revealed a significant decrease in bat velocity for the control and weighted condition with a significant correlation between the two conditions, which indicates the results were consistent for all participants (Otsuji et al., 2002). Subjective judgment by the participants showed that they not only perceived that the weighted bat was heavier than the normal bat, but

also that the swing felt slower than that for the Control condition (Otsuji et al., 2002).

Results for the after-effects of a weighted bat swing revealed a significant decrease in the velocity of the first swing in the post-weighted condition when compared with the control condition. Subjective evaluation of heaviness of the bat and that of swing speed during the post-weighted trials indicated that for the first swing the rating of heaviness was 4.4 and the rating of speed was 4.3 therefore, the participants perceived the bat to be clearly lighter and the swing to be faster than those of the Control condition (Otsuji et al., 2002). After the third swing seven participants and after the fifth swing five participants reported that the bat was slightly heavier and the swing was slightly faster mean values for heaviness and speed after the third swing were 3.9 and 3.8, respectively, and those after the fifth swing were 3.6 and 3.5 respectively (Otsuji et al., 2002).

These results are consistent with that of Scott & Gray (2010), in that, significant difference was observed for only the first swing, with the remaining swings being consistent with the control condition. Decrease in the batting velocity on the very first swing following swings with the weighted bat can be attributed to an altered pattern of batting movements, which most likely occurred by the motor command formed during the swings with the weighted bat (Otsuji et al., 2002).

After one swing with the normal bat, the swing velocity returned to that of the Control condition, and thus at least from the view of mechanical aspects of batting, contribution of the motor commands for swinging the weighted bat had been largely nullified (Otsuji et al., 2002), which may indicate that the hitter possessed a calibration state that could have been induced when using the standard game bat following the first swing. As Scott & Gray (2010) stated, negative effects could potentially be absent once the hitter consistently practice switching between the heavy warm-up bat and the standard bat. Over the years of practice from performing the same warm-up, it appears to be that the hitter possessed a motor command for such a movement and/or warm-up (Otsuji et al., 2002), thus requiring him only one swing to overcome the altered motor pattern and return to normal when using a standard bat following a weighted warm-up.

Moreover, a mismatch between the results of sensory judgment and measures in the actual batting trials suggests that the participants experienced sensory illusions for both load to the limb and speed of motion after the swings with the weighted bat (Otsuji et al., 2002) which led to a decrease in swing velocity for the first swing. This mismatch caused a psychological effect which persisted much longer than the effects on the motor command being that after the fifth swing, 63% of the participants described that the sensation of the swing

speed was increased and the bat appeared to weigh less (Otsuji et al., 2002). This kinesthetic illusion from swinging the weighted bat seems to last longer than motor command alterations, and could possibly give a psychological advantage to the hitter which cannot go unrecognized.

Kinesthetic aftereffect (illusion) is defined as a perceived modification in the shape, size, or weight of an object or a perceptual distortion of limb position, movement, or intensity of muscular contractions as a result of an experience with a previous object (Sage, 1984; Nakamoto et al., 2012). Nakamoto, Ishii, Ikudome, and Ohta (2012) investigated the kinesthetic aftereffects of a weighted tool on movement correction in baseball batting. Eight male college baseball players participated in this study. A horizontal track with 200 LED's which turned on and off in sequence which simulated the linear motion of an object (baseball) so the participants could clearly identify the continuous motion of an impending target. In order to achieve a kinesthetic effect, a 42oz weighted bat was used as a warm-up swing prior to swinging a 30oz standard bat. Kinematic data was collected via a three-dimensional motion analysis system sampling at 400Hz with the three-dimensional coordinate system defined as the Y axis as the batting direction towards the pitching rubber, the Z axis as the vertical axis, and the X axis as perpendicular to the Y axis (Nakamoto et al., 2012).

Participants performed a coincident timing task which included a warning visual stimulus (illumination of 5 LED's) which was followed by 3 moving target stimulus conditions after a three second interval with five seconds before the next warning stimulus. Three practice swing conditions which utilized different bat weights and procedures before the coincident timing task which included the normal condition which involved three practice swings with a standard bat. A weighted bat condition which contained three practice swings with a weighted bat and finally, the recalibration condition which involved three swings with weighted bat followed by three with the standard bat, with all the test trials in the coincident timing task utilizing a standard weight bat (Nakamoto et al., 2012).

Participants were instructed to stand at the front edge of the LED track to familiarize themselves with the procedure under three stimulus conditions: unchanged, temporal, and spatial changed conditions. Subsequently, participants performed thirty coincident timing swings for each of the conditions, which were subdivided into six simulation swing tasks (blocks), which were completed at maximal effort after three swings with either the standard or weighted bat (Nakamoto et al., 2012). These blocks included three equivalent stimulus conditions. Following six swings in the simulation task, the participants were then asked to make subjective judgments of the

heaviness of the bat during the swing and the speed of the swing compared to that of typical weights and speeds via a 5 point Likert scale derived from Otsuji et al. (2002). For analysis, four dependent variables were used: subjective perception in a bat swing, swing velocity, and the absolute temporal (ATE) and spatial (ASE) errors (Nakamoto et al., 2012).

Results from the analysis on subjective bat swing speed and weight revealed statistical significance in the mean score of subjective feelings of swing speed; specifically, the weighted and recalibration conditions had significantly higher scores than the normal condition. Also, subjective feelings of bat weight revealed a significant difference between the normal and the other two conditions, that is, the participants felt that they swung faster and that the bat was lighter after the practice swing in the weighted and recalibration conditions (Nakamoto et al., 2012). Next, results from the analysis on bat speed revealed significant main effects for stimulus and practice, specifically swing velocity in the unchanged condition was faster than the changed velocity and location conditions, while in the comparisons among practice swing conditions, there were slightly significant differences between the weighted and normal bat conditions (Nakamoto et al., 2012).

Finally, results from the analysis on coincident temporal and spatial errors revealed a significant stimulus x practice swing interaction. Analysis of the main effects showed that in the velocity unchanged condition, the ATE in the recalibration condition was smaller than those of the normal and weighted bat conditions (Nakamoto et al., 2012). In the velocity changed condition, the ATE in weighted condition was larger than in the normal condition and recalibration condition, the ATE in the changed condition was larger than that in the unchanged condition.

Participants in this study felt that the bat to be lighter following swing with a weighted bat than in the normal condition and perceived swing velocity was somewhat faster in the weighted condition than in the normal condition which indicated that subjective mismatches occurred with bat weight but not with swing speed (Nakamoto et al., 2012). Although mismatches were not observed for swing speed, ATE was greater in the weighted condition than in the normal condition and only in the changed velocity task which indicated kinesthetic aftereffect showed a selective effect of perceptual-motor control that requires movement timing correction (Nakamoto et al., 2012) which may have been caused by varying swing velocities respective of the condition.

Decreasing the swing velocity in the changed condition indicates that hitters correct their motor plan before the motor pattern

generator implements the last planned movement. Following practice swings with weighted bats, baseball hitters are unable to correct their movement duration (Nakamoto et al., 2012) by slowing swing velocity up until the final decision. The authors stated that the acute effect of the kinesthetic aftereffect that selectively influences the movement timing correction process is caused by the failure to decrease swing velocity by altering the preprogrammed motor command (Nakamoto et al., 2012).

This selective effect does not fully explain Reyes and Dolny (2009) and Southard and Groomer (2003) who stated that using a weighted bat alters muscular strength and swing motor patterns, respectively, because adaptations to the peripheral system affect swing velocity regardless of stimulus conditions (Nakamoto et al., 2012). However, an explanation may be the result of central system influences and the kinesthetic aftereffects affects effector anticipation. Sensory awareness is increased when the actual sensation (afferent information) mismatches predicted sensations (i.e., efference copy) and vice versa (Blakemore, Frith, & Wolpert, 1999; Nakamoto et al., 2012).

Subjective perceptions of increased swing velocities in the weighted condition suggests that hitters employed the efference copy that predicted a slower swing than that of the actual swing velocity

(Nakamoto et al., 2012); meaning that the practice swing with the weighted bat altered the formulation of the efference copy. The authors concluded that warm-ups with a weighted tool create adverse effects for the movement (re)programming processes in interceptive action (Nakamoto et al., 2012). This proposes that performing warm-ups with a weighted object (bat), during a task that requires target interception; it's not the peripheral system that is affected, but rather the central nervous system.

2.5 Location of Weight (Moment of Inertia- MOI)

Inertia is defined as the ability to resist motion or a measure of how difficult it is to change the velocity of an object by applying a force and is usually expressed in terms of mass. The greater the inertia of an object (i.e., the more mass an object has), the more difficult it is to change its velocity. Mass is defined as a property of an object (i.e., a given object will have the same mass regardless of where in the universe it is located) (Russell, 2007). Weight is defined as a force, specifically the force that an object experiences when gravity acts on the implement (Russell, 2007). The previous terms are slightly different but often used interchangeably. Moment of Inertia (MOI) is a measure of how difficult it is to change the rotational velocity of an object which is rotating about a pivot point (Russell, 2007). The larger the moment-of-inertia, the more difficult it is to change the rotational speed of the

object. The value of the MOI depends on the total mass of the object as well as the way in which that mass is distributed about the pivot point (Russell, 2007).

For a player to overcome inertia, the location of the pivot point becomes important. There are three main phases of the baseball swing (Russell, 2007); however, for the scope of the present study only the first two phases will be reviewed. Phase one which is where the hitter's rotation of the bat-arm system are about a pivot point near the hitters shoulders (Russell, 2007). There is no rotation of the bat with respect to the player's wrists during this phase. The player's arms and the bat remain at ninety degree angle with respect to each other as the bat is pulled around and forward (Russell, 2007). During this first phase of the swing the actual weight of the bat (or mass) is more important since the player must overcome the inertia of the bat to begin moving towards the object, but the bat does not change its orientation to the player as it moves (Russell, 2007). Differences in actual bat weight would be noticeable to a player during this portion of the swing, but differences in the balance point wouldn't matter because the bat is not rotating with respect to the player's hands or wrists (Russell, 2007).

Phase two, which contains the wrist rotation, is where the bat undergoes two types of rotation: small amount of rotation of the bat-

arm system about a pivot point near the shoulders and more importantly rotation of the bat about a point that appears to be centered near the player's wrists (Russell, 2007). During this part of the swing, when the bat is primarily rotating about the point near the hitter's wrists, the actual weight (mass) of the bat is less important than the swing weight (MOI). During this phase of the swing, two bats with the same actual weight (mass) but different swing weights (MOI) would be easily distinguished (Russell, 2007). The bat with the lighter swing weight (or decreased MOI) will be easier to control and easier to produce a quick whip-like action to achieve greater bat velocity. If the bat is end-loaded, the larger rotational inertia of the bat will make it more difficult for a hitter to swing. This "wrist-rotation" phase of the swing is what generates the maximum bat speed just prior to collision with the ball (Russell, 2007).

Performance of the sporting instrument (i.e. baseball bat), is defined as the outgoing ball speed which depends both on the intrinsic power of the instrument and the speed with which the instrument is swung (Cross & Nathan, 2009). It has also been observed that intrinsic power depends upon the conventional MOI of the instrument about an axis near the handle end (Cross & Nathan, 2009). It is often argued that light instruments can be swung faster (Russell, 2007; Cross & Nathan, 2009) than heavy instruments to make up for their lack of

intrinsic power. The most conclusive indication comes from an experiment conducted by Smith, Broker, and Nathan, (2003) using a series of sixteen altered softball bats swung by twenty elite softball players. The bats were specially constructed for the study to distinguish a dependence of swing speed on mass from MOI.

Therefore, ten of the bats had the same mass and different values of the MOI, while the other ten had the same MOI and different mass (Smith, Broker, & Nathan, 2003). The results showed that the maximum swing speed for any given player depended on the MOI about an axis (Smith, Broker, & Nathan, 2003) through the handle end of the bat. Having a larger MOI of the bat, the more difficult it is to swing the bat quickly, while a lower MOI bat may be swung with greater speed and greater control (Russell, 2007). Recent field studies of real players swinging baseball bats (Fleisig, Zheng, Stodden, & Andrews, 2002) have demonstrated that the speed with which a player can swing a bat depends very strongly on the moment-of-inertia of the bat.

Fleisig, Zheng, Stodden, & Andrews, (2002) conducted a study utilizing seventeen male collegiate baseball players and seventeen female collegiate softball players as volunteer participants. Five variations of a Louisville Slugger TPS softball bat were used, including an unmodified bat, a light weight added into the handle, a heavier

weight added into the handle, a light weight added into the barrel, and a heavier weight added into the barrel (Fleisig, Zheng, Stodden, & Andrews, 2002). Five similar variations of an Easton B5 baseball bat were used, including an unmodified bat, a light weight added into the handle, a heavier weight added into the handle, a light weight added into the barrel, and a heavier weight added into the barrel (Fleisig, Zheng, Stodden, & Andrews, 2002). Nine male participants were also randomly selected to test two lighter unmodified bats - an Easton BE40W and a Louisville Slugger TPX (Fleisig, Zheng, Stodden, & Andrews, 2002) with all data obtained by a four-camera 200 Hz automatic digitizing motion analysis system. After taking one or two warm-up swings with a given bat, the hitter took three swings for data collection.

Results showed for both baseball and softball, significant differences for linear velocity between various bats. Differences in angular velocity were not significant. Decreased bat mass properties correlated with increased bat velocity. Baseball bat linear velocity had a significant negative correlation (increase MOI about the handle-decrease bat velocity) about the handle with bat MOI (swing weight), but not with bat weight (mass). The results presented show that linear velocity varied significantly among various bats, and the variations in

velocity were significantly related to bat MOI, not bat mass (Fleisig, Zheng, Stodden, & Andrews, 2002).

Evidence suggests that bat velocity is influenced by batted ball velocity and resulting batter performance (Fleisig, Zheng, Stodden, & Andrews, 2002). Interestingly, many researchers infer that batted ball velocity depends on a number of factors such as: bat velocity, pitching velocity, coefficient of restitution (CoR), the bats flexural properties, and the location of impact on the bat (Watts & Bahill, 2000). During bat to ball impact, momentum ($p = \text{mass} \cdot \text{velocity}$) is transferred from the bat to the ball. The increase in bat velocity results in an increase in the bat's momentum, which in turn is transferred to the batted ball, thus increasing the batted ball velocity (Fleisig, Zheng, Stodden, & Andrews, 2002). Reducing a bat's weight (mass) and MOI (swing weight) inversely decreases the bat's effective mass, resulting in decreased ball velocity (Fleisig, Zheng, Stodden, & Andrews, 2002).

Cross & Nathan, (2009) findings show a curve where the batted ball speed increases rapidly as the swing weight (MOI) increases ($> 0.1 \text{ kg}\cdot\text{m}^2 - 0.2 \text{ kg}\cdot\text{m}^2$) levels off ($0.3 \text{ kg}\cdot\text{m}^2$), then falls slowly ($\sim 0.5 \text{ kg}\cdot\text{m}^2$) as the swing weight (MOI) of the bat is increased. This indicates that there is a tradeoff between effective mass and swing speed (MOI), which influenced by the swing weight in opposite ways (Cross & Nathan, 2009). This inverse relationship can be explained by a bat with

a very small swing weight, such as a broomstick which would be easy to swing but would have a small effective mass (Cross & Nathan, 2009). Furthermore, a bat with a very large swing weight, such as a heavy steel bar, would be more difficult to swing but would have a larger effective mass (Cross & Nathan, 2009). The optimum swing weight (MOI), producing the largest batted ball speed, would lie somewhere between the two extremes ($\sim .22 \text{ kg}\cdot\text{m}^2$) and depends somewhat on the incoming ball speed (Cross & Nathan, 2009).

Bats used in amateur play (level of play less than MLB) tend to have a swing weight (MOI) slightly smaller than the optimum ($\sim 18 \text{ kg}\cdot\text{m}^2$), on the rising part of the curve mentioned above, suggesting that batters could improve their maximum batted ball speed by using a bat with a larger swing weight (MOI) (Cross & Nathan, 2009); however, hitters tend not to do so. Baseball hitters are able to distinguish between bat speed and bat quickness. Bat speed has to do with the speed at the moment of the collision (Cross & Nathan, 2009), while bat quickness has to do with the bat acceleration, which affects the batter's ability to control the movement of the bat and get it into the hitting zone quickly (Cross & Nathan, 2009). While a batter can hit a ball harder with a swing weight (MOI) near the top of the curve ($\sim 0.2 \text{ kg}\cdot\text{m}^2$), the hitter is likely to hit a ball solidly more often with a somewhat smaller swing weight (MOI).

The preference by hitters to use a less than optimum swing weight (MOI) provides a logical explanation for the NCAA rule that specifies a lower limit but not an upper limit on the allowable swing weight (MOI) of a bat (Cross & Nathan, 2009). If a baseball organization is interested in limiting bat speed, it could consider establishing a regulation for minimum MOI (swing weight) (Fleisig, Zheng, Stodden, & Andrews, 2002). Although bat mass is not as strongly correlated to bat velocity as MOI (swing weight) (Fleisig, Zheng, Stodden, & Andrews, 2002; Cross & Nathan, 2009; Russell, 2007), regulating low mass/low MOI (swing weight) with extra mass located within the handle of the bat, because MOI is a function of mass and mass distribution, would reduce the bat velocity and would comply with NCAA regulations (Fleisig, Zheng, Stodden, & Andrews, 2002; Bahill, 2004). This can be a practical compromise between players and organizations (Fleisig, Zheng, Stodden, & Andrews, 2002) because a large amount of mass may be added to the handle of a bat without significantly altering the bat's MOI (swing weight) (Russell, 2010) and subsequently slowing the speed of the swing.

Alternately, Kim and Hinrichs, (2008) testing twenty subjects under three different warm-up conditions: Standard Bat serving as the control (CO), over weighted Arm (OA), and over-weighted Bat (OB). Subjects performed a total of 35 swings, consisting of seven sets in the

laboratory with each set including five swings. The first set was five trials of the standard bat swing with ball contact. It was defined as the pre-warm-up set of swings and was compared with other post-warm-up sets. After a 5 minute rest, a warm-up set was applied. The order of warm-up conditions was decided by a counter-balanced design between the CO, OA, and OB conditions in advance (Kim and Hinrichs, 2008). After the first warm-up set, there was a 2 minute break before post-warm-up swings with a standard bat. In addition, a 5 minute break was given before the next warm-up. The interval between trials was 20 seconds. An Advanced Motion Measurement 3-D system consisting of twelve electromagnetic sensors sampling at a rate of 240 Hz was used to collect position data of the full body dynamic motion and calculate angular and linear velocities (Kim and Hinrichs, 2008).

Kim and Hinrichs, (2008) findings support, that during warm-up swings the bat speed of the CO condition was significantly faster than that of the OA condition and the OB condition. However, the OA warm-up increased bat speed more than the CO and OB warm-ups, although these differences were not statistically significant due to large variation across subjects (Kim and Hinrichs, 2008). The bat speed following the OA warm-up was slightly improved over pre-warm-up while that following the OB warm-up was slightly reduced (Kim and Hinrichs, 2008). Thus the over weighted bat (OB) warm-up seemed not

beneficial to the bat swing speed similar to recent study findings (Kim & Hinrichs, 2008; Southard & Groomer, 2003). In conclusion this study showed no benefit of the over weighted bat warm-up in the on-deck circle for improving bat speed. Rather, players may want to try an over weighted arm warm-up instead even though it was not proven statistically, a slight improvement was observed (Kim & Hinrichs, 2008).

This conclusion contradicts that of Bahill (2004) which revealed that most players would benefit from an end loaded bat. Although it was noted that adding additional weight to the distal portion of the bat would not provide any advantageous effects, with regard to batted ball speeds, an end loaded bat would be beneficial. If it is beneficial for players to use an end loaded bat like Bahill (2004) recommends, the warm-up should follow the rule of sport specificity, with training (warm-up) mimicking that of a game situation.

2.6 Specificity of Training

In the previous section, principles such as moment of inertia (MOI) and laws of conservation of angular and linear momentum were introduced and used to explain the location of the weight located on the implement and the energy transfer of the implement to the pitched ball, respectively. Biomechanics and physics have utilized these principles to ground research and explain phenomena such as energy

transfer and conservation, however, the fields of strength and conditioning and exercise physiology are grounded by principles such as overload, progression, and more importantly specificity (Rhea, et al., 2008). These principles provide exercise scientists and professionals a foundation for the structure and design of exercise training programs to maximize performance (Rhea, et al., 2008) for complex situations such as preparing an athlete for a full season of play, to appropriate warm-up routines performed prior to a game situation.

The term warm-up in sport is defined as a period of preparatory exercise to enhance subsequent competition or training performance (Hedrick, 1992). A pre-game warm-up for team sports typically includes a period of sub maximal running, static stretching of the major muscle groups and sport specific movements incorporating various range of motion (ROM) exercises with skill-based drills executed at, or just below game intensity (Young & Behm, 2002).

Baker, (1996) has stated, and DeRenne et al. (2001) have confirmed that training exercises can be classified into three categories; *general, special, and specific* (Szymanski, DeRenne, & Spaniol, 2009). To develop optimal power, a combination of these three training exercises should be implemented. *General* training increases overall strength by using traditional exercises such as

squats, bench press, and rows (Szymanski et al., 2008; Szymanski, DeRenne, & Spaniol, 2009). *Special* training is designed to develop power, once strength has been improved through the use of explosive exercises (i.e. medicine ball throws) (Szymanski et al., 2008; Szymanski, DeRenne, & Spaniol, 2009). Finally, *specificity* of training attempts to provide a training stimulus that mimics the exact movements, range of motion (ROM), and muscular contractions as actual game motions while utilizing the same bioenergetic system (aerobic or anaerobic) during warm-up and while performing the activity during a game situation (Sergo & Boatwright, 1993; Szymanski, DeRenne, & Spaniol, 2009).

The principle of specificity states that the training program needs to be sport or fitness specific (Rhea, et al., 2008). Furthermore, Baker, (1996) states that specificity of training infers that there is a positive transfer of training effect when resistance training exercises are close to or identical to the sport skill-specific ROM. Thus, exercises for hitting must be compatible with the alternating acceleration and deceleration movements and consistent with game time speeds in order exploit changes that will allow the hitter to enhance performance (DeRenne, Buxton, Hetzler, & Ho, 1995).

In the sports community when enhancing hitting skills, the use of underweighted or over weighted baseball bats are frequently used

as a means to warm the hitter up immediately prior to stepping into the batter's box. Literature has recommended various training programs which are specific to the muscles involved during game time motions, (Montoya et al., 2009) however, it would also seem appropriate to have warm-up programs adhere to the same rule of sport specificity.

It is important to note, that the term 'training' used above does not imply a training regimen commonly used by strength and conditioning coaches over an extended period of time. Properly constructing a periodized resistance training regimen for the baseball athlete or investigating the optimal long-term training protocol is beyond the scope of this paper. The term 'training' is synonymous with complex training during the pre-competition warm-up immediately prior to participating in a game time situation. This complex training utilizes alternating sets of heavy and light resistances to increase power output (Baker, 2003a). Previous research studies have reported that alternating heavy and light resistance sets improves muscle power for both upper and lower body exercises (Young, W, Jenner, A, and Griffiths, 1998; Baker, 2003a).

2.6.1 Train to perform

The use of weighted bats is based on the theory of complex training, where sets of heavier and lighter resistances are alternated to elicit a potential increase in muscle performance (Baker, 2003a; Reyes

& Dolny, 2009). The principle behind the heavy facilitation set in complex training is that skeletal muscle tends to be more explosive after being subjected to near-maximal contractions (Baker, 2003a). This postactivation potentiation (PAP) as a result of the heavy facilitation set has demonstrated increased power in subsequent movements such as bench press throw distance, broad jump lengths, vertical jump heights, and medicine ball throw distance (Young, Jenner, & Griffiths, 1998; Baker, 2003a; Gourgoulis et al., 2003). PAP enhances motor-neuron pool excitability and increased recruitment of motor units, which leads to greater power (Baker, 2003a, Ebben, 2002). The weighted bat is the hitter's equivalent of a complex 'warm-up' as they prepare to maximize bat velocity when hitting (Reyes & Dolny, 2009).

Several suggestions relative to resistance load order have been proposed (Reyes & Dolny, 2009). Baker, (2001) suggests based upon findings in the effect of an ascending versus a descending order of loads during explosive bench press throws. Results indicated that an ascending order resulted in a significantly higher power output for the heaviest load, whereas the descending order resulted in a significantly higher power output for the lightest load (Baker, 2001). It was concluded that when attempting to increase power with a lighter weight, it is best to warm up in a descending order of resistance, with

the final weight being the one you intend to use for the test or sport (Baker, 2001). The heavy warm-up load stimulates the neural system, allowing for greater muscle activation during the light bat swings (Reyes & Dolny, 2009). However, in contradiction to Baker, (2001), Reyes & Dolny, (2009) found positive effects for all protocols. The authors recommend the specific weighted bat warm-up order of standard, light, heavy because this particular protocol enhanced bat velocity by 6%.

Based on the specificity principle, one may have expected the use of only the standard bat to be beneficial because previous research has demonstrated that the use of heavy bats acutely decreases bat velocity (Otsuji, Abe, & Kinoshita, 2002; Southard & Groomer, 2003). This may be from changing the bat's MOI, which may alter the motor pattern of the actual swing (Reyes & Dolny, 2009). Reyes & Dolny, 2009 confirmed that alteration of the motor pattern did not occur; in fact, the warm-up consisting of all heavy bat swings resulted in the second highest bat velocity percentage improvement among the eight protocols utilized.

However, Southard & Groomer, (2003) findings confirm the notion of the alteration of motor patterns when interpreting the findings from various theoretical viewpoints. When batters swing with a different moment of inertia, they could select a different motor program or re-

parameterize an existing program on the basis of information gained prior to or during the swing (Southard & Groomer, 2003). The authors interpreted these findings through the dynamical systems perspective which suggests that pattern change is a function of the interaction among constraints from the individual, the environment, and the task (Southard & Groomer, 2003). Considering the baseball bat is an extension of the performer, the increase in the MOI leads to a reorganization of the movement pattern, or coordination is reorganized when the bat's MOI is scaled to a critical threshold (Southard & Groomer, 2003). DeRenne et al., (1992) findings that bat velocity changes only when weights are varied by more than 10% may be an integral clue in quantifying the critical value which changes the swing pattern.

However, observation indicated that the swing pattern change was not permanent and in the instances which the weighted warm-up condition was followed by a condition in which warm-up involved the standard bat, bat velocity was greater and the swing pattern demonstrated distal lag (Southard & Groomer, 2003). The practical message involving the study by Southard & Groomer, (2003) utilizing the theory of sport specificity, is that baseball hitters are better served warming up with the bat that they intend to use during competition. With inconsistent conclusions as to which bat/protocol to utilize during

the warm-up immediately prior to entering the batter's box, the sport specific warm-up protocol needs to be fully understood when attempting to maximize performance through maximizing individual bat velocity.

When preparing to hit in a real game situation, a player in the on-deck circle is not only trying to warm up the muscles used during the swing but also attempting to maximize bat velocity when they step up to the plate. Traditionally, this has been accomplished through the use of a heavy 'donut' attached to the bat; however, it is not agreed upon in the literature as to which device is more advantageous to the athlete prior to stepping into the batter's box. Various studies revealed different conclusions leaving large inconsistencies in the literature as to which device elicits the greatest post warm-up velocity. Similar inconsistencies in the literature were observed for the location of the MOI when swinging a baseball bat. Suggestions of additional weight being added to the upper arm proposed by Kim and Hinrichs, (2008) during warm-up swings resulting in a slight but non-significant improvement in bat velocity, while the opposite was proposed by Bahill, (2004) recommending that most hitters would benefit from an end loaded bat. With inconsistencies however, it is mutually accepted that bat MOI has a stronger relationship with bat velocity than bat mass.

Finally, inconsistencies were observed as to which bat/protocol to utilize prior to stepping in the batter's box still remains unclear. Southard & Groomer, (2003) relayed the message to plan to use the bat one would use during a game situation, while Reyes and Dolny, (2009) recommend using any combination of the protocols alternating weights from heavy, standard, light. However it has been suggested by those studies who have found significance that a player should warm up with a specific, weighted bat that is identical to or very close to the same weight ($\pm 10\%$ or 27-34oz) (DeRenne et al., 1992) as the standard game bat (30oz), and evenly distributed and should replicate his standard range of motion while swinging a bat at high game velocity to adhere to the sport specificity notion (DeRenne et al., 1992). The evenly distributed bat was only investigated in an underweight condition; therefore, the interest of the current researcher is to investigate the effects of an evenly distributed bat on subsequent swing velocity post-warm up.

With inconsistencies in the literature regarding which device is more advantageous to increase post warm-up bat velocity, location of MOI, and the fact that research using an evenly distributed bat is relatively virgin, further investigation on an evenly distributed bat is warranted. Use of an evenly distributed bat could not only add to the body of knowledge of warm-up devices for a hitter, but could also have

practical implications to the batter in selecting an appropriate device to maximize bat velocity and subsequently improving batting performance.

Chapter III

METHODS

The purpose of this chapter is to outline and effectively describe the methodologies associated with the single-subject experimental design of the study. The subsequent sections will explain and define in detail: operational definitions (3.1), dependent variables (3.2), limitations (3.3), delimitations (3.4), instrumentation (3.5), participants (3.6), general procedures (3.7), familiarization (3.8), warm-up procedures (3.9), experimental procedures (3.10), data reduction (3.11) and data analysis (3.12).

3.1 Operational Definitions

1. Bat Velocity- Speed at which the bat is moving toward the incoming pitch in miles per hour (MPH).
2. Bat Trajectory- Path that the baseball bat follows through 2-dimensional space (Z and Y axes) as a function of time; obtained from a single reflective marker located on the tip of the barrel of the bat.
3. Evenly Distributed- Set amount of weight evenly spread throughout the length of the custom wooden bat.
4. College Age- subjects for this study will be between the ages of 18-24, typically what is seen in most collegiate undergraduate programs.

5. Position Player- A player who routinely participates on the field of play and has at bats during a game situation. Pitchers are excluded because more time is spent working on pitching mechanics than swinging a bat.

3.2 Dependent Variables

1. Bat Velocity- Speed at which the bat moves toward the incoming pitch.
2. Bat Trajectory- Path that a moving object (bat) follows through space as a function

3.3 Limitations

1. Participants may have not maximally swung the baseball bat during the control condition with the 30 ounce baseball bat.
2. Participants may have not maximally swung the over weighted baseball bat during the specific warm-up.
3. Participants may have not maximally swung the 30oz bat during the posttest.
4. Participants may not have been completely transparent in answering all questions on the health history injury form, Par-Q and informed consent documents.

5. All markers may not have been correctly placed on appropriate anatomical locations from trial to trial to accurately represent the data.
6. Participants may not have followed all written and verbal instructions.
7. Lack of EMG data

3.4 Delimitations

1. Participants from East Stroudsburg University varsity baseball team.
2. College aged male within the range of 18-24 years of age.
3. Participant who is free from musculoskeletal injury for the past 8 months.
4. Participant who has completed the Health History Injury form (Appendix C), Physical Activity Readiness Questionnaire (Appendix G) and Informed Consent (Appendix B).

3.5 Instrumentation

An eight-camera (MX-40) motion analysis system (Vicon, Oxford, UK) was used sampling at 100 Hz to capture the swings performed by the participant. In order to calculate joint angles in the sagittal, frontal and transverse planes a full body Plug-in-Gait marker setup was used. This involved placing 39 retro- reflective markers on

the following anatomical landmarks while participants were in a neutral static position: left front head, right front head, left back head, right back head, 7th cervical vertebrae, 10th thoracic vertebrae, clavicle, sternum, right back (middle of right scapula), left shoulder (acromioclavicular joint), right shoulder, left upper arm, right upper arm, left elbow, right elbow, left forearm, right forearm, left wrist (thumb side), right wrist (thumb side), left wrist (pinkie side), right wrist (pinkie side), left index finger, right index finger, left anterior superior iliac spine, right anterior superior iliac spine, left posterior superior iliac spine, right posterior superior iliac spine, left knee, right knee, left thigh, right thigh, left ankle, right ankle, left lower 1/3 of shank, right lower 1/3 of shank, left toe, right toe, left heel, right heel. Values obtained from each marker were then used by Vicon Nexus software package (Version 1.0, Vicon, Oxford, UK) to calculate spatiotemporal characteristics associated with the movement observed.

Dynamic calibration via a 5 Marker Wand (Vicon, Oxford, UK) was utilized prior to capturing data. The 5 Marker Wand was placed where the participants were standing to address the baseball resting on the tee to set the volume of the cameras where the movement was captured. Following setting the camera volume, the 5 Marker Wand was dynamically wielded throughout the three-dimensional space where the movement of the swing occurred for a period of 30 seconds

to give the Vicon Nexus system an idea of the geometry of the capture volume. The result of the dynamic wielding of the 5 marker Wand calibration resulted in an image error of $>2\text{mm}$ for all cameras.

The global reference frame was defined as the three-dimensional coordinate system where the movement of interest took place. Each of the three axes was perpendicular to each other. For this study, the position of the bat marker with respect to the tee marker in the positive y-axis was the most critical because it was used to obtain the velocity of the baseball bat at the instant of bat-ball contact. It was defined as the direction from home plate to the pitching rubber and parallel to the batting box. When looking at the positive Y direction, positive Z was defined as pointing superiorly and positive X was defined as pointing to the right.

3.6 Participants

Three right-hand swinging participants, were utilized for this study (age= $19.3\text{yrs} \pm 1.5\text{yrs}$; height= $1.74\text{m} \pm .13\text{m}$; mass= $81\text{kg} \pm 20.4\text{kg}$; baseball experience= 14.2 ± 1.3). The participants were volunteers from the campus of East Stroudsburg University of Pennsylvania, specifically the University varsity baseball team. Recruitment fliers (Appendix A) located around Koehler Fieldhouse, where practices normally take place, was utilized in order to assist in the recruitment process. The participants self-identified as being free

from musculoskeletal injury 8 months prior to the commencement of the study via the Health history injury form (Appendix C).

3.7 General Procedures

Prior to the start of data collection all procedures were approved by the Institutional Review Boards of Seton Hall University (Appendix E) and East Stroudsburg University of Pennsylvania (Appendix D), where data collection took place. After responding to the recruitment flyer, the interested participants reported to East Stroudsburg University's Biomechanics laboratory to fill out an Informed Consent Form (Appendix B), Health history injury form (Appendix C) and a Physical Activity Readiness Questionnaire (Par-Q) (Appendix F). Following the completion of the forms, the participants were given a thorough and detailed description of the procedures involved within the study. Also, the participants were presented a schedule of time commitments and the opportunity to ask questions about the study.

After completion of the Informed Consent, Health history injury form and PAR-Q forms, a neutral third party Professor from East Stroudsburg University's Exercise Science department evaluated all documents for correct signatures and dates. Once inclusion criteria have been met and all forms are properly filled out and signed, the participants had anthropometric measurements taken by the principle investigator, which were needed for Vicon software analysis. The

specific anthropometric measurements are as follows: shoulder width, shoulder offset, elbow width, wrist width hand thickness, knee width, ankle width, leg length, height, and weight; which were obtained using anthropometric calipers and a standard tape measure. Following the anthropometric measurements, the participant was randomly assigned a numbered code to protect anonymity. All personal information was stored on a password protected USB flash drive under the specific subjects' coded folder. After all information was saved, the participants began the familiarization trials in the Biomechanics laboratory.

3.8 Familiarization

A familiarization session took place one day prior to data collection. The participants were asked to wear neoprene (spandex) baseball sliding shorts and a neoprene t-shirt for the familiarization session as well as subsequent visits to the Biomechanics laboratory.

Retro-reflective markers were placed on the participants at the specific anatomical locations as described above. On the locations which were covered by clothing, the markers were attached via Velcro; for the parts of the body which were exposed, 3M two-way tape was used to secure the marker to the anatomical landmark. The exposed locations were thoroughly cleaned with an alcohol pad to rid the location of body oils to allow the marker to be firmly attached to the skin.

The reason for the familiarization was to allow the participants to become accustomed to having retro-reflective markers attached to the body while performing a typical swinging motion. The principle investigator was responsible for conducting all components of the familiarization testing session.

3.9 Warm-up Procedures

The participants reported to the Biomechanics laboratory on the day of testing. Following the application of the markers explained above, the participants were instructed to swing a standard, 30oz game bat 3 times for maximal velocity which served as the baseline or control condition. Following the control condition, after a 10 minute rest period, the participant performed a standardized *general* warm-up consisting of overhead and behind the back stretching with a randomly assigned warm-up device for a period of one minute (DeRenne, Ho, Hetzler, & Chai, 1992). The warm-up devices are as follows: a standard game bat (33inch/30oz- serving as the control), a weighted bat with a 16 ounce 'donut' slid onto the barrel of the standard 33in/30oz baseball bat with the total weight being 46 ounces, a standard 33in/30oz bat with a 24 ounce Pow'r sleeve with total weight being 54 ounces and two custom 33in/30oz wooden baseball bats, which were evenly distributed bats with internal weight added throughout the length of the bat. The weight of the first evenly

distributed bat was the same total weight (46 ounces) as the weight of the bat with the additional weight of the 'donut'. 16oz of additional weight was added throughout the entire length of the 33in/30oz bat. The weight of the second evenly distributed bat was the same total weight (54 ounces) as the weight of the bat with the additional weight of the Pow'r sleeve. 24oz of additional weight was added throughout the entire length of the 33in/30oz bat.

The order of the weighted bats were randomized and counterbalanced ensuring that participants used each bat over 5 days of data collection. Each session was 24 hours apart to minimize carryover effects. The procedures of DeRenne, Ho, Hetzler & Chai, (1992) were strictly followed, with the only alterations being the custom weighted, evenly distributed baseball bats.

Following the *general* warm-up with a specific bat, the participants were then instructed to perform a *specific* warm-up which consisted of swinging a specific weighted device 4 consecutive times as fast as possible in a typical batting motion. Following the *general* and *specific* warm-up, the participant was then instructed to pick up the standard 33in/30oz bat and swing it 2 times in a way that is comfortable to the participants. The principle investigator was responsible for conducting all components of the warm-up session

3.10 Experimental Procedures

Following the 2 swings of the standard bat, the participant was then instructed to swing the standard 33in/30oz bat 3 times while hitting a baseball off of a standard baseball hitting tee, with 20 seconds of rest between each swing. The baseball, which was supported by the tee, was located in an area which is consistent with a fastball down the middle of home plate. The height of the baseball was belt high, which is the location that is ideal for maximum contact with the ball. The above process will be repeated until all warm-up bats are utilized by the participants, with subsequent swings with the standard bat for each variation of the warm-up device. The principle investigator was responsible for conducting all components of the experimental session.

3.11 Data Reduction

All kinematic data were smoothed using a generalized cross-validated quintic spline procedure prior to further analyses. Furthermore, a fill gaps spline procedure was utilized to interpolate the location of the bat marker from when the cameras 'missed' the position of the bat marker to when the camera 'sees' the bat marker in the Y axis. Following the spline procedures, data was then exported to an excel spreadsheet for further analysis. Smoothed position data was then differentiated using the first central difference method to provide the linear velocity value of the marker located at the distal end of the

barrel of the bat in the Y and Z axes. Next, the Pythagorean Theorem was utilized to obtain the resultant vector between the Z and Y axes, and then multiplied by 2.23694 to convert the data in meters/second to miles per hour. Finally, bat trajectory was obtained by taking the inverse tangent of the velocity value in the Z axis divided by the velocity value in the Y axis and then multiplied by 57.3 to convert radians into degrees.

3.12 Data Analysis

All analysis was performed using Microsoft Excel 2010 for Windows. To find significant differences within the data, the Shewart Chart method, commonly referred to as the 2 standard deviation method, was utilized to assess variability within the baseline phase by calculating the mean and STDEV of data points within that phase (Portney and Watkins, 2008). Standard deviation was then added and subtracted from the mean to obtain the upper and lower limits of the two standard deviation range. Significance is evident when a minimum of two consecutive data points' falls outside the upper and lower limits of the two standard deviation range.

Chapter IV

RESULTS

4.1 Baseball Bat Velocity with Respect to Ball Contact for All Participants.

This section utilized the graphs constructed using the 2 standard deviation method with the solid black line representing the mean and the two red lines representing the upper and lower limits of the 2 standard deviation range. Significant differences are revealed when at least two consecutive data points fall outside the 2 standard deviation range. All baseline and post warm-up values were obtained at the instant of ball contact, with the intervention values obtained while swinging the bat toward the direction of the baseball tee as if they were making contact with the ball; however contact was not present due to the fact that the participant was swinging the weighted warm-up device.

4.1.1. Participant 1 Velocity for Each Condition

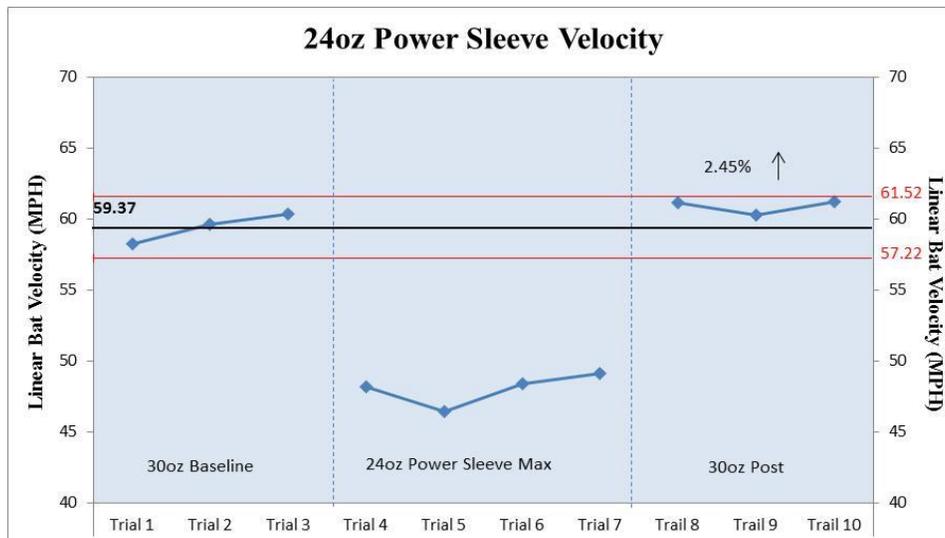


Figure 1. Participant 1 24oz Power Sleeve Velocity. This graph illustrates the 24oz Power Sleeve velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 1, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, an increase in velocity in the posttest of 2.45% was observed which equates to the participant swinging the bat 1.43mph faster than the baseline leaving a velocity of 60.8mph during the posttest when comparing to the baseline.

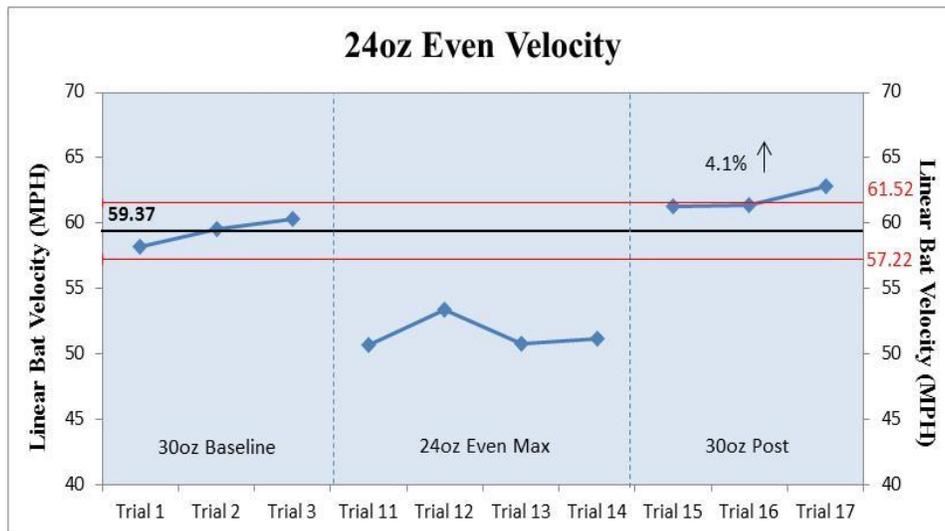


Figure 2. Participant 1 24oz Evenly Distributed Velocity. This graph illustrates the 24oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 2, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball bat. Furthermore, an increase in velocity in the posttest of 4.1% was observed which equates to the participant swinging the bat 2.43mph faster than the baseline leaving a velocity of 61.8mph during the posttest when comparing to the baseline.

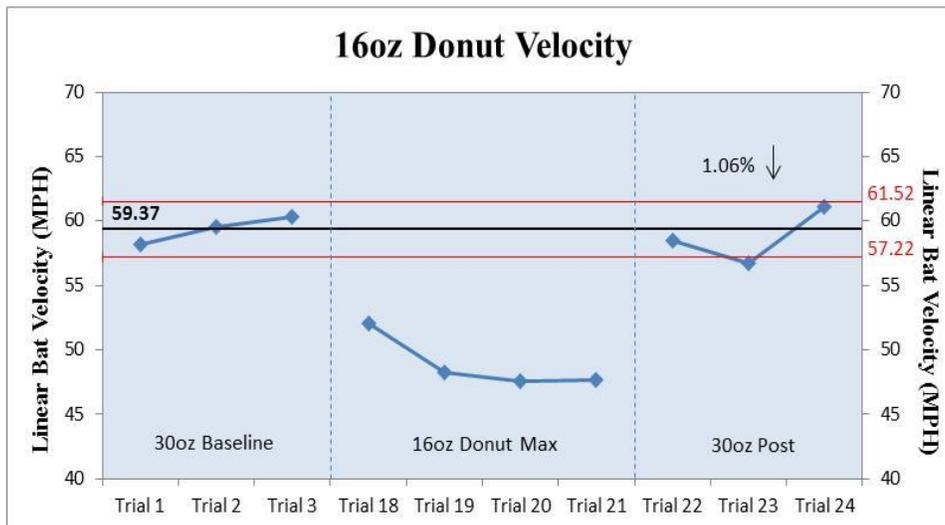


Figure 3. Participant 1 16oz Donut Velocity. This graph illustrates the 16oz donut velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 3, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, a decrease in velocity in the posttest of 1.06% was observed which equates to the participant swinging the bat .66mph slower than the baseline leaving a velocity of 58.71mph during the posttest when comparing to the baseline.

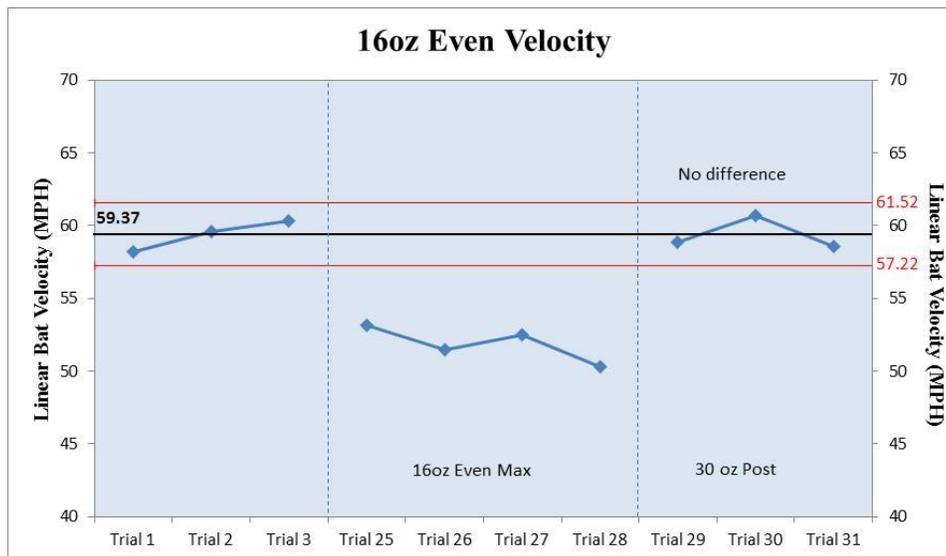


Figure 4. Participant 1 16oz Evenly Distributed Velocity. This graph illustrates the 16oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 4, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball bat. Furthermore, there was no difference in percent difference, meaning during the posttest the participant was swinging the exact same velocity as was observed in the pretest when comparing to the baseline.

Table 1.

Participant 1 Summary of Velocity Data

Condition	M Velocity	Significance	% Difference	Velocity Difference (MPH)	Posttest Velocity (MPH)
24oz Power Sleeve	59.37	NS	2.45+	1.43+	60.80
24oz Even	59.37	NS	4.10+	2.43+	61.80
16oz Donut	59.37	NS	1.06-	0.66-	58.71
16oz Even	59.37	NS	No Difference	No Difference	59.37

Note. + And – symbols indicate an increase or decrease in post warm-up bat velocity, respectively.

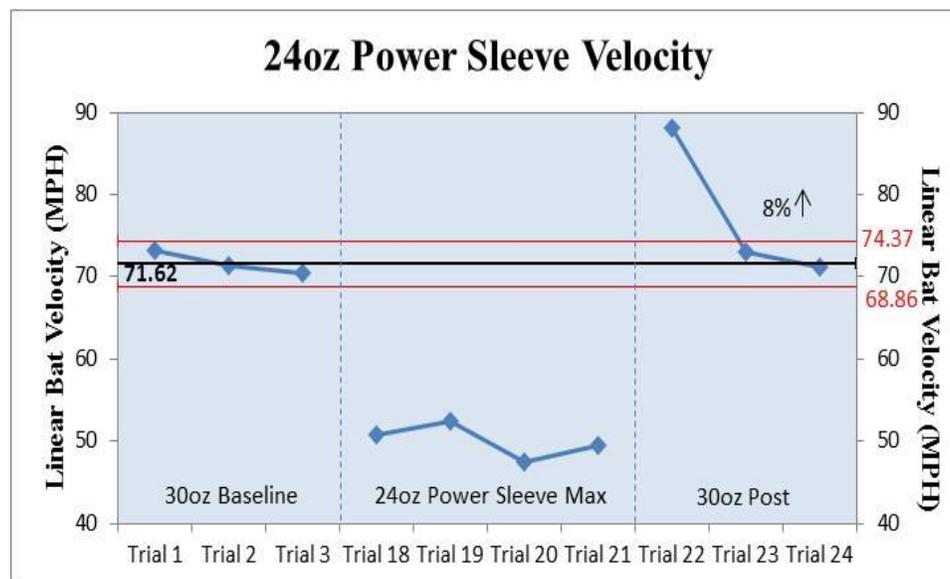
4.1.2. Participant 2 Velocity for Each Condition

Figure 5. Participant 2 24oz Power Sleeve Velocity. This graph illustrates the 24oz Power Sleeve velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 5, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, an increase in velocity in the posttest of 8% was observed which equates to the participant swinging the bat 5.76mph faster than the baseline leaving a velocity of 77.38mph during the posttest when comparing to the baseline.

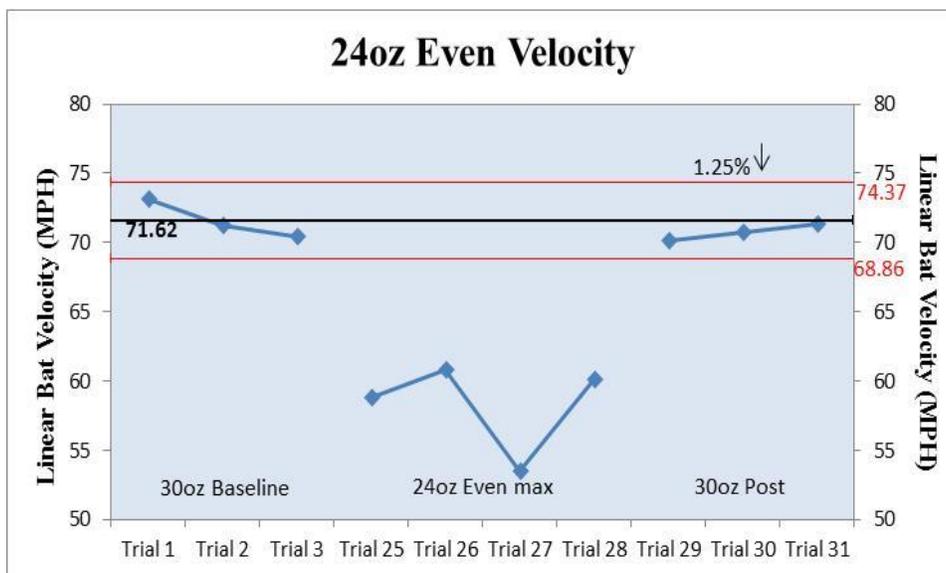


Figure 6. Participant 2 24oz Evenly Distributed Velocity. This graph illustrates the 24oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 6, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball

bat. Furthermore, a decrease in velocity in the posttest of 1.25% was observed which equates to the participant swinging the bat .9mph slower than the baseline leaving a velocity of 70.7mph during the posttest when comparing to the baseline.

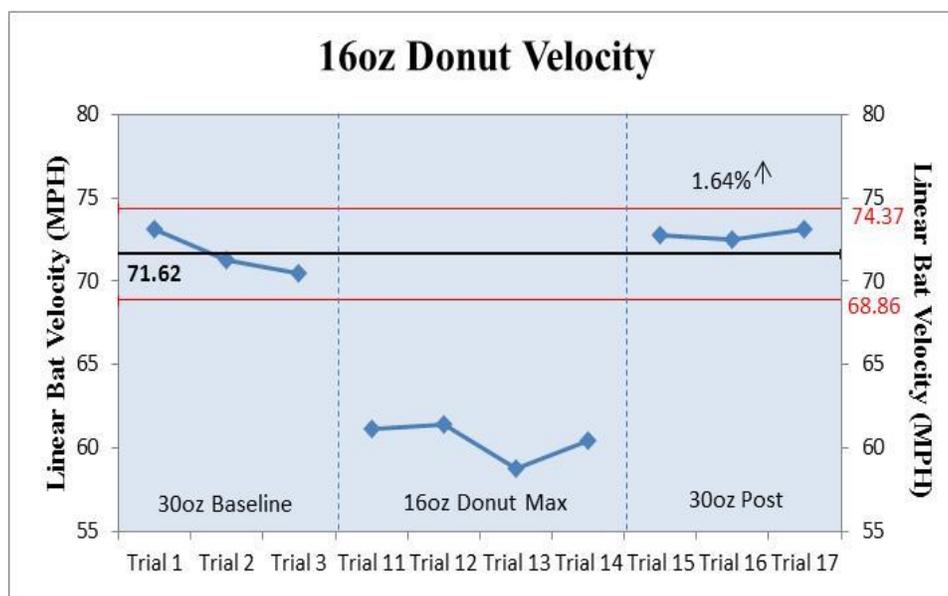


Figure 7. Participant 2 16oz Donut Velocity. This graph illustrates the 16oz donut velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 7, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, an increase in velocity in the posttest of 1.64% was observed which equates to the participant swinging the bat 1.18mph faster than the baseline leaving a velocity of 72.8mph during the posttest when comparing to the baseline.

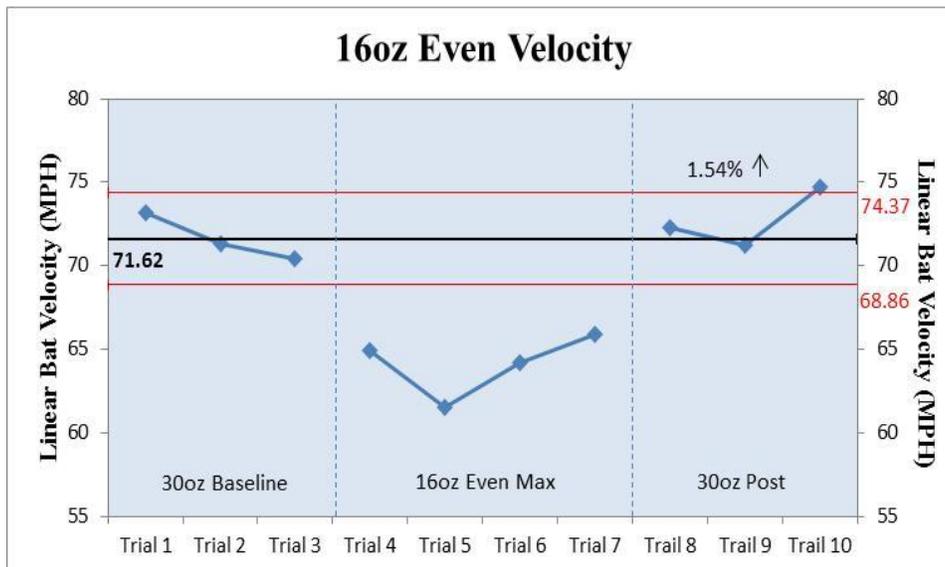


Figure 8. Participant 2 16oz Evenly Distributed Velocity. This graph illustrates the 16oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 8, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball bat. Furthermore, an increase in velocity in the posttest of 1.54% was observed which equates to the participant swinging the bat 1.10mph faster than the baseline leaving a velocity of 72.7mph during the posttest when compared to the baseline.

Table 2.

Participant 2 Summary of Velocity Data

Condition	<i>M</i> Velocity	Significance	% Difference	Velocity Difference (MPH)	Posttest Velocity (MPH)
24oz Power Sleeve	71.62	NS	8.00+	5.76	77.38
24oz Even	71.62	NS	1.25-	0.90	70.70
16oz Donut	71.62	NS	1.64+	1.18	72.80
16oz Even	71.62	NS	1.54+	1.10	72.70

Note. + And – symbols indicate an increase or decrease in post warm-up bat velocity, respectively.

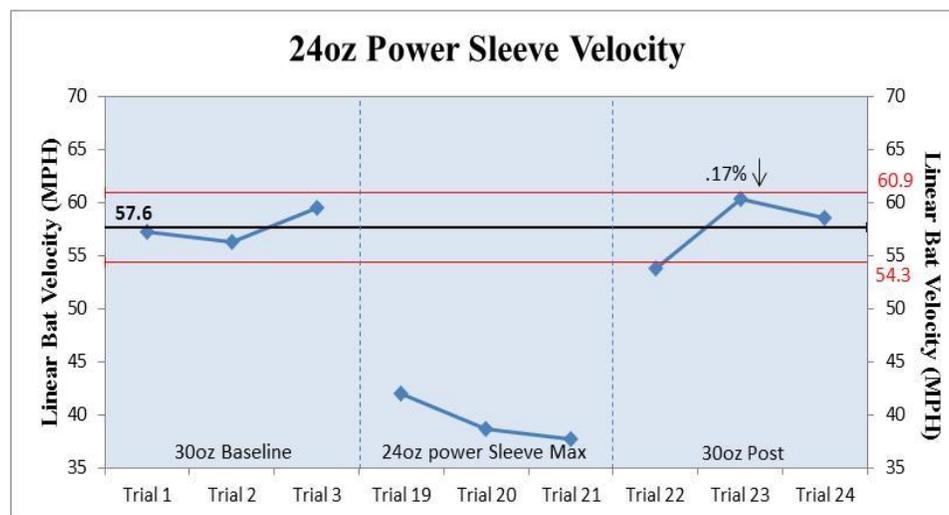
4.1.3. Participant 3 Velocity for Each Condition

Figure 9. Participant 3 24oz Power Sleeve Velocity. This graph illustrates the 24oz Power Sleeve velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 9, there was no significant difference between the baseline and the posttest phases, however a significant difference

was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, a decrease in velocity in the posttest of .17% was observed which equates to the participant swinging the bat .1mph slower than the baseline leaving a velocity of 57.5mph during the posttest when comparing to the baseline.

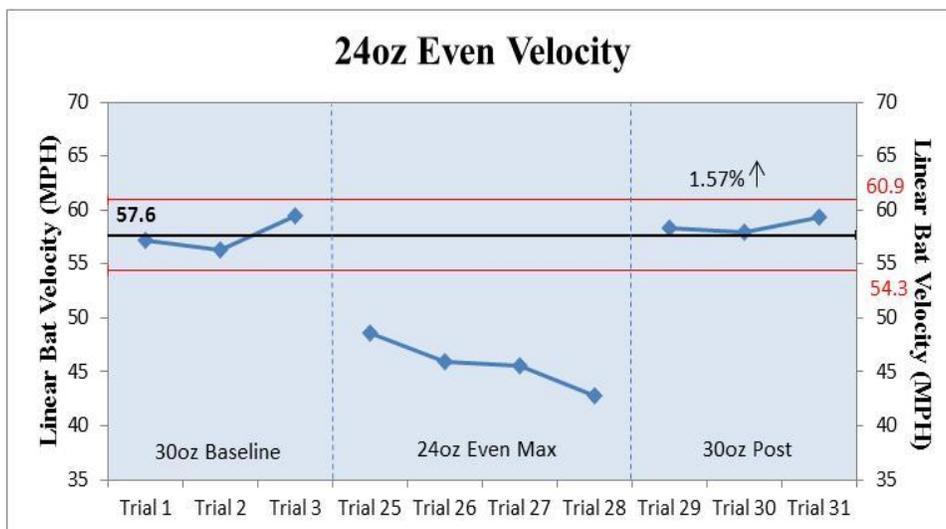


Figure 10. Participant 3 24oz Evenly Distributed Velocity. This graph illustrates the 24oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 10, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball bat. Furthermore, an increase in velocity in the posttest of 1.57% was observed which equates to the participant swinging the bat

.86mph faster than the baseline leaving a velocity of 58.51mph during the posttest when comparing to the baseline.

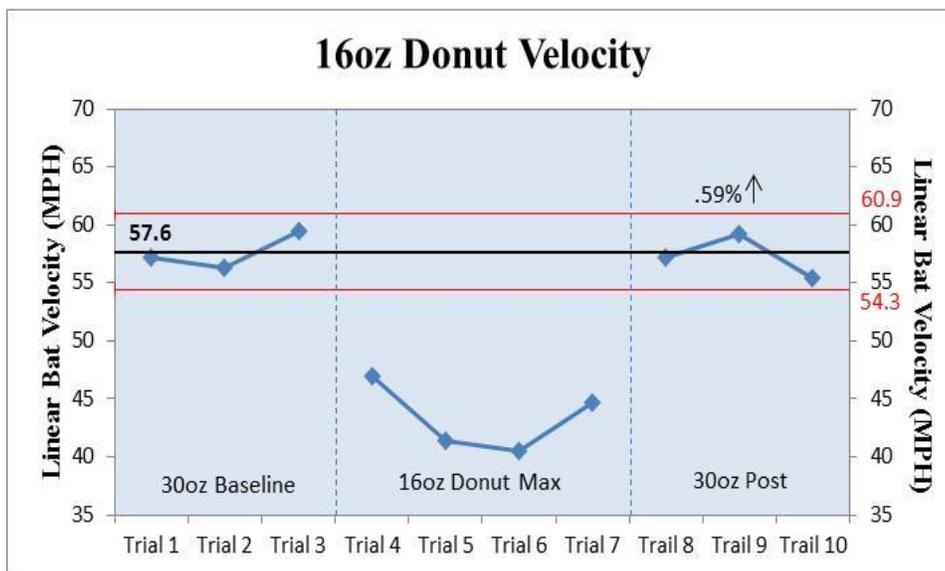


Figure 11. Participant 3 16oz Donut Velocity. This graph illustrates the 16oz donut velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 11, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added to the distal portion of the bat. Furthermore, an increase in velocity in the posttest of .59% was observed which equates to the participant swinging the bat .34mph faster than the baseline leaving a velocity of 57.26mph during the posttest when comparing to the baseline.

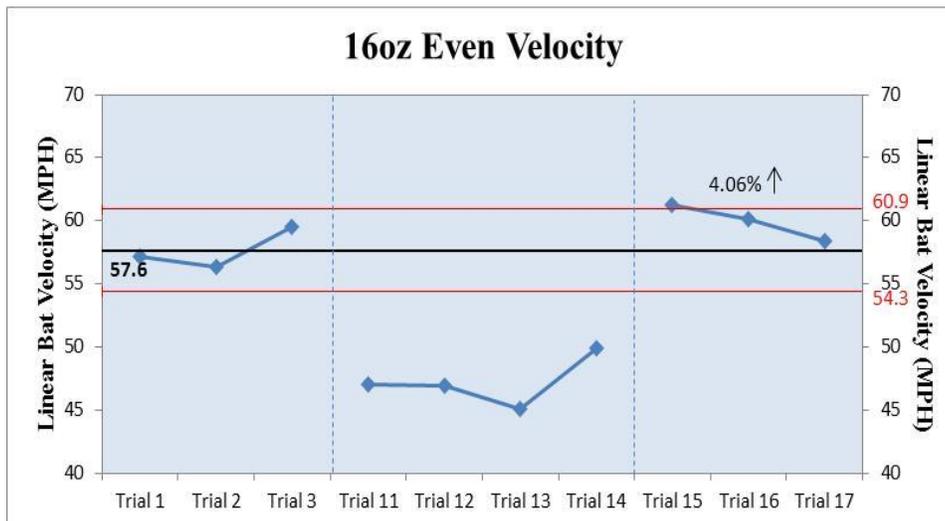


Figure 12. Participant 3 16oz Evenly Distributed Velocity. This graph illustrates the 16oz Evenly Distributed velocity for the baseline, intervention and posttest. Also, the percent difference is illustrated in the posttest.

As seen in Figure 12, there was no significant difference between the baseline and the posttest phases, however a significant difference was observed when swinging the baseball bat with the additional weight added throughout the length of the custom wooden baseball bat. Furthermore, an increase in velocity in the posttest of 4.06% was observed which equates to the participant swinging the bat 2.34mph faster than the baseline leaving a velocity of 59.94mph during the posttest when compared to the baseline.

Table 3.

Participant 3 Summary of Velocity Data

Condition	<i>M</i> Velocity	Significance	% Difference	Velocity Difference (MPH)	Posttest Velocity (MPH)
24oz Power Sleeve	57.60	NS	0.17-	0.10	57.50
24oz Even	57.60	NS	1.57+	0.86	58.51
16oz Donut	57.60	NS	0.59+	0.34	57.26
16oz Even	57.60	NS	4.06+	2.34	59.94

Note. + And – symbols indicate an increase or decrease in post warm-up bat velocity, respectively.

4.2 Baseball Bat Trajectory at Ball Contact for All Participants.

This section utilized the graphs constructed using the 2 standard deviation method with the solid black line representing the mean and the two red lines representing the upper and lower limits of the 2 standard deviation range. Significant differences are revealed when at least two consecutive data points fall outside the 2 standard deviation range. All baseline and post warm-up values were obtained at the instant of ball contact, with the intervention values obtained while swinging the bat toward the direction of the baseball tee as if they were making contact with the ball; however contact was not present due to the fact that the participant was swinging the weighted warm-up device.

4.2.1. Participant 1 Trajectory for Each Condition

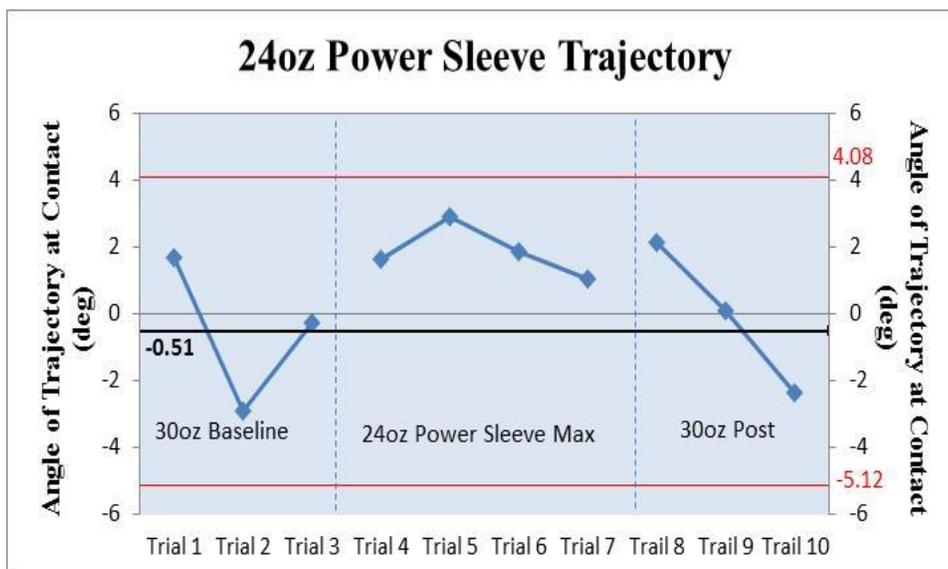


Figure 13. Participant 1 24oz Power Sleeve Trajectory. This graph illustrates the 24oz Power Sleeve trajectory for the baseline, intervention and posttest.

As seen in Figure 13, there were no significant difference between the baseline and the posttest phases. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

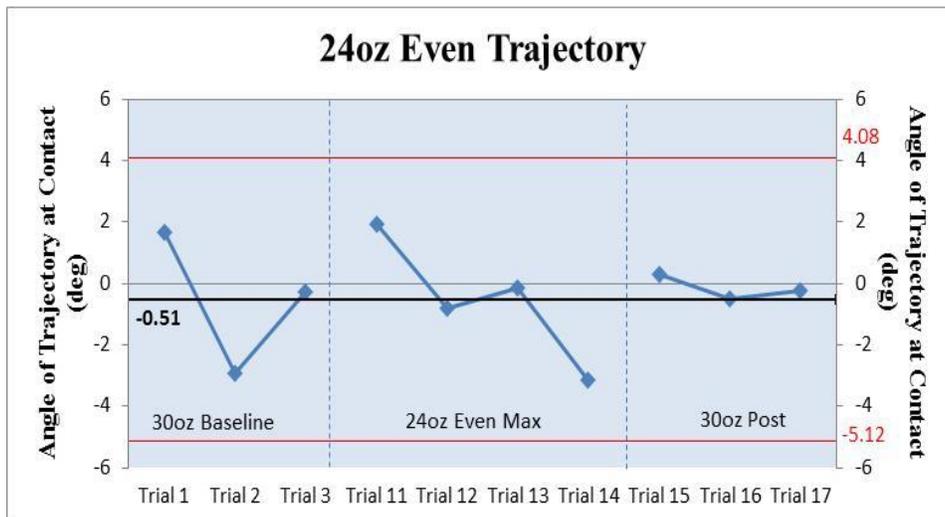


Figure 14. Participant 1 24oz Evenly Distributed Trajectory. This graph illustrates the 24oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 14, there were no significant difference between the baseline and the posttest phases. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

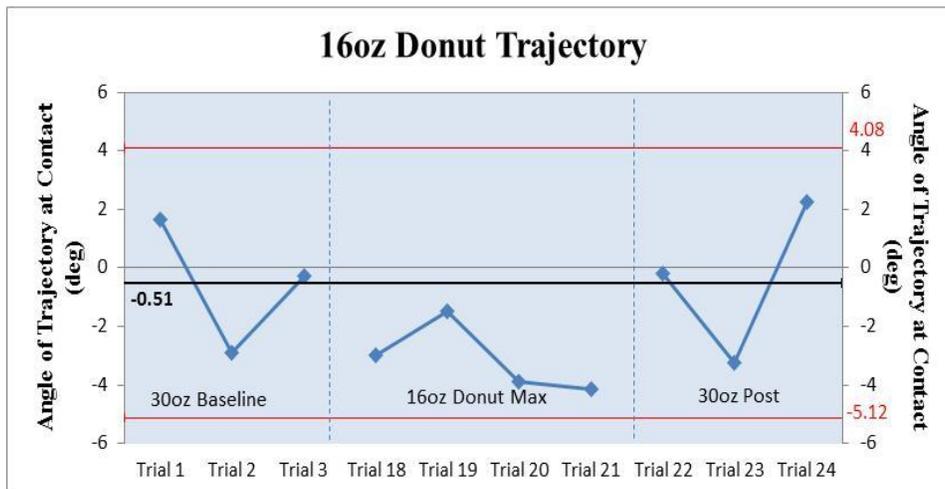


Figure 15. Participant 1 16oz Donut Trajectory. This graph illustrates the 16oz Donut trajectory for the baseline, intervention and posttest.

As seen in Figure 15, there were no significant difference between the baseline and the posttest phases. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

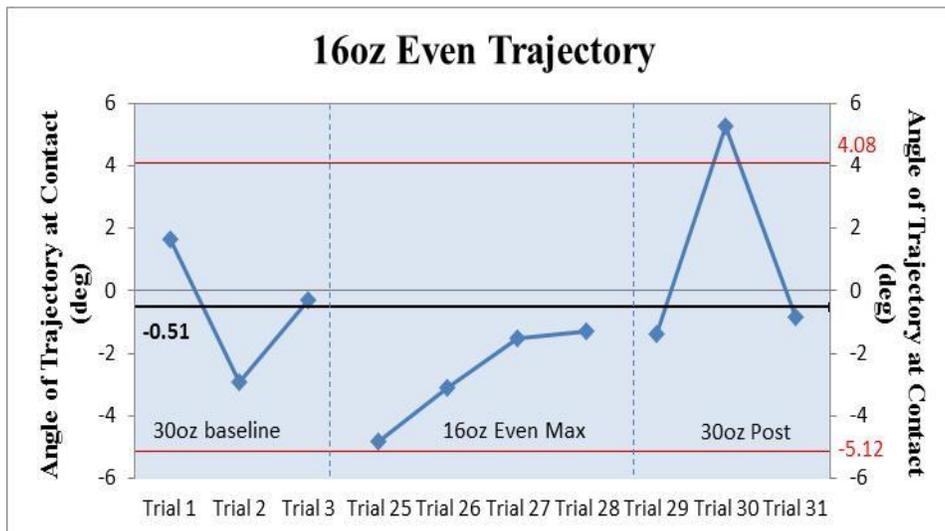


Figure 16. Participant 1 16oz Evenly Distributed Trajectory. This graph illustrates the 16oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 16, there were no significant difference between the baseline and the posttest phases. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

4.2.2. Participant 2 Trajectory for Each Condition

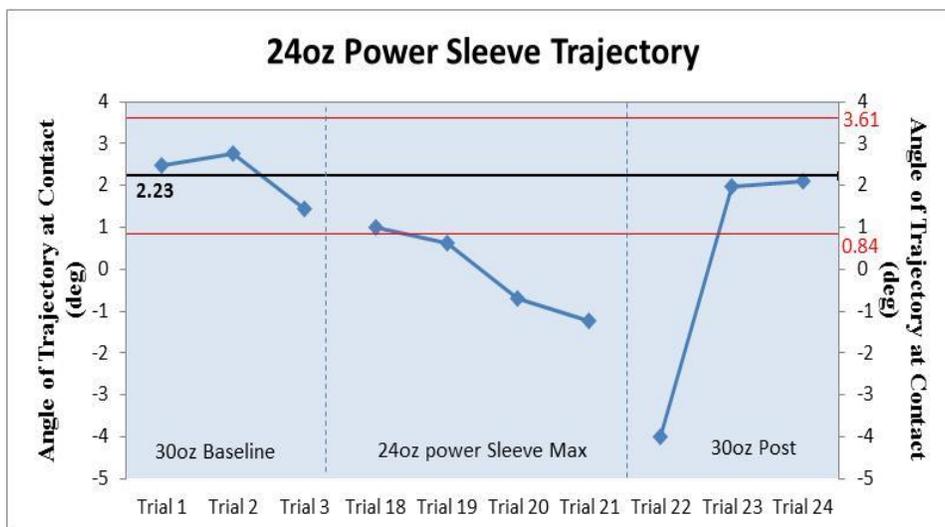


Figure 17. Participant 2 24oz Power Sleeve Trajectory. This graph illustrates the 24oz Power Sleeve trajectory for the baseline, intervention and posttest.

As seen in Figure 17, there were no significant difference between the baseline and the posttest phases. However, significant differences were observed while dynamically wielding the weighted device. It should be noted that the participant was not contacting the ball and the significant differences could be attributed to the increase in bat diameter with the use of the power sleeve when swinging in a typical batting motion when swinging the bat toward the baseball tee. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

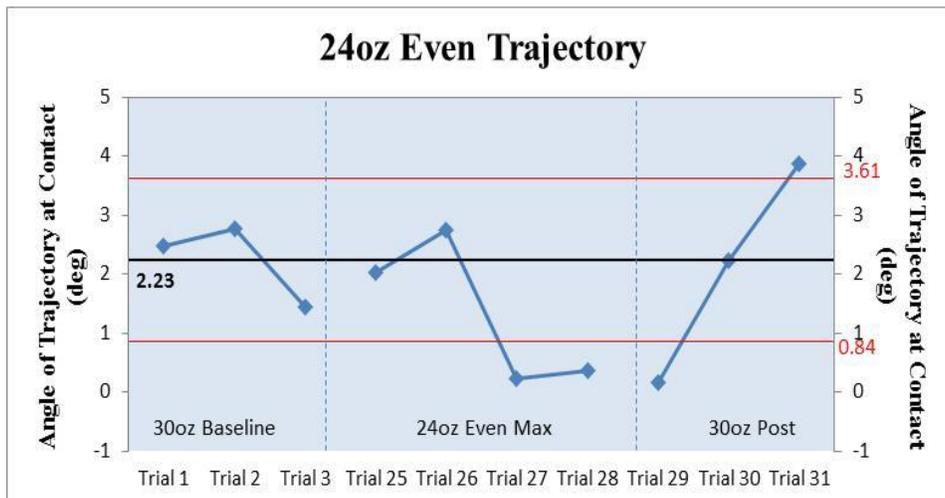


Figure 18. Participant 2 24oz Evenly Distributed Trajectory. This graph illustrates the 24oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 18, there were no significant difference between the baseline and the posttest phases. However, significant differences were observed while dynamically wielding the weighted device which may be attributed to the fact there was no object to contact when swinging the bat toward the tee. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

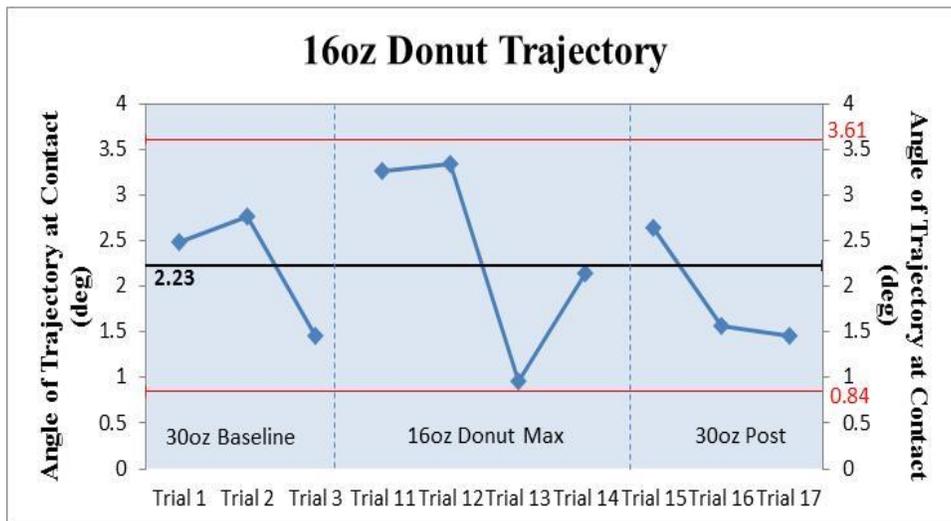


Figure 19. Participant 2 16oz Donut Trajectory. This graph illustrates the 16oz donut trajectory for the baseline, intervention and posttest.

As seen in Figure 19, there were no significant difference between the baseline and the posttest phases. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

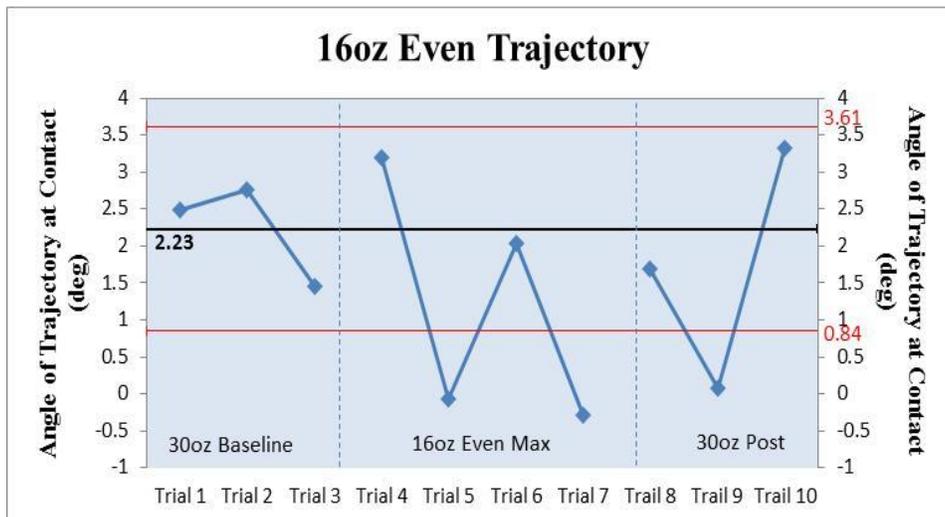


Figure 20. Participant 2 16oz Evenly Distributed Trajectory. This graph illustrates the 16oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 20, there were no significant difference between the baseline and the posttest phases. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

4.2.3. Participant 3 Trajectory for Each Condition.

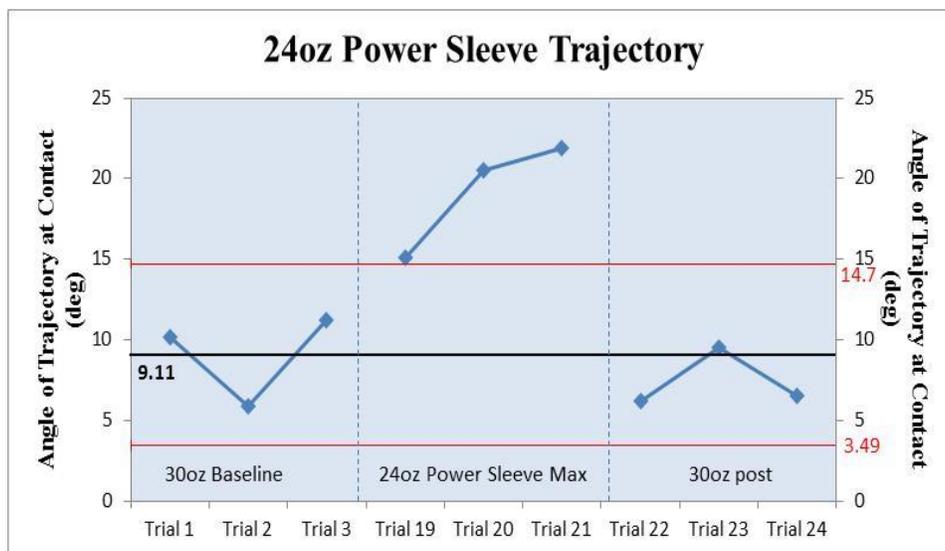


Figure 21. Participant 3 24oz Power Sleeve Trajectory. This graph illustrates the 24oz Power Sleeve trajectory for the baseline, intervention and posttest.

As seen in Figure 21, there were no significant difference between the baseline and the posttest phases. However, significant differences were observed while dynamically wielding the weighted device. It should be noted that the participant was not contacting the ball and the significant differences could be attributed to the increase in bat diameter with the use of the power sleeve when swinging in a typical batting motion when swinging the bat toward the baseball tee. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.



Figure 22. Participant 3 24oz Evenly Distributed Trajectory. This graph illustrates the 24oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 22, there were no significant difference between the baseline and the posttest phases. However, significant differences were observed while dynamically wielding the weighted device which may be attributed to the fact there was no object to contact when swinging the bat toward the tee. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

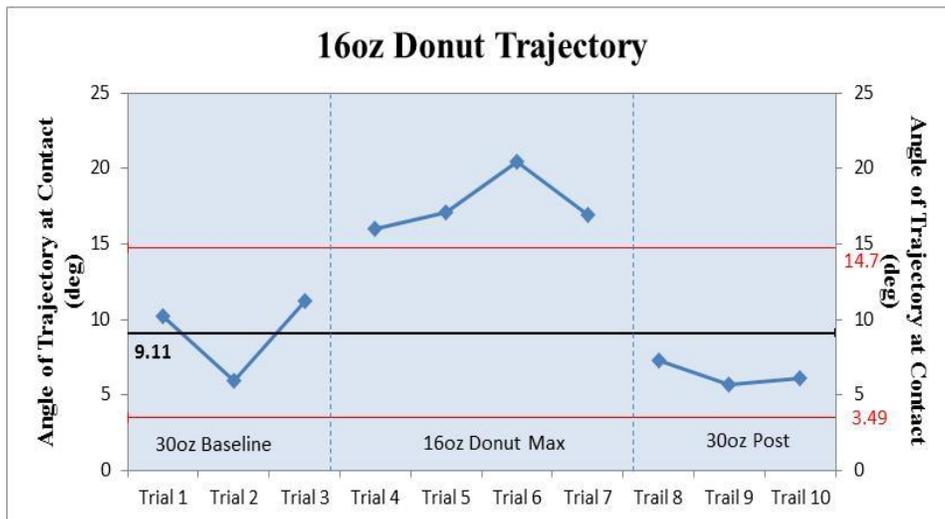


Figure 23. Participant 3 16oz Donut Trajectory. This graph illustrates the 16oz donut trajectory for the baseline, intervention and posttest.

As seen in Figure 23, there were no significant difference between the baseline and the posttest phases. However, significant differences were observed while dynamically wielding the weighted device. It should be noted that the participant was not contacting the ball and the significant differences could be attributed to the increase in bat diameter with the use of the donut when swinging in a typical batting motion when swinging the bat toward the baseball tee. Distally located, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee.

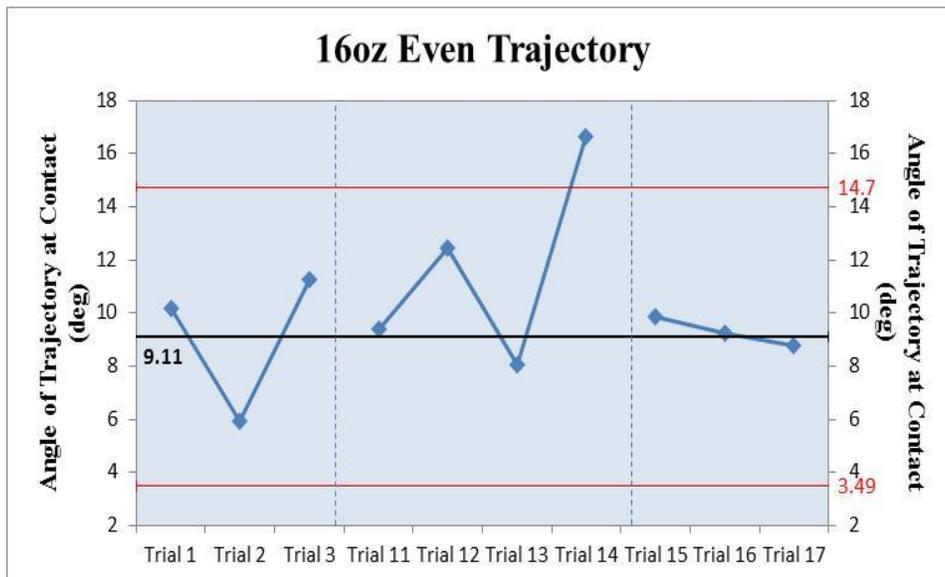


Figure 24. Participant 3 16oz Evenly Distributed trajectory. This graph illustrates the 16oz evenly distributed trajectory for the baseline, intervention and posttest.

As seen in Figure 24, there were no significant difference between the baseline and the posttest phases. Evenly distributed, additional weight dynamically wielded by the participant during the intervention phase caused no differences in the post warm-up trajectory when attempting to hit a stationary ball off of a standard batting tee

4.3 Location of Ball Contact with Respect to Horizontal Midline of the Ball for All Participants.

This section shows tables constructed using the location of the bat marker in the Z axis (in millimeters) showing where the participant contacted the ball for the baseline phase and each conditions posttest. The numbers illustrated within the tables, in millimeters, represent the location of contact on the ball relative to horizontal midline of the ball. A positive value is indicative of striking the ball above the horizontal midline of the ball, whereas a negative value is indicative of striking the ball below the horizontal midline of the ball.

Table 4.

Participant 1 Lowest Point of Bat Trajectory and Location of Contact Relative to Horizontal Midline of the Ball

Condition	Contact at Lowest Point of Bat Trajectory	Location of Contact Relative to Ball Midline (mm)
Baseline	YES	4.80+
Baseline	YES	0.18+
Baseline	YES	7.10-
24oz Power Sleeve	YES	1.62-
24oz Power Sleeve	YES	14.76-
24oz Power Sleeve	YES	8.50-
24oz Even	YES	10.60+
24oz Even	YES	8.91+
24oz Even	YES	18.65+
16oz Donut	YES	12.60-
16oz Donut	YES	2.90+
16oz Donut	YES	26.00+
16oz Even	YES	5.91-
16oz Even	YES	21.20+
16oz Even	YES	25.60-

Note. + and – symbols indicate contact in millimeters above and below the horizontal midline of the ball, respectively.

As seen in Table 4, participant 1 consistently struck the ball at the lowest point in the bats trajectory in the Z axis for all conditions agreeing with Gray (2002) and Tabuchi, Matsuo, and Hashizume, (2007). Furthermore, the numbers in millimeters for the baseline and 24oz power Sleeve conditions dictate that the ball was struck within the range of 29.00mm (19.00mm below the balls horizontal midline for an

effective fly ball, as well as 10mm above the balls horizontal midline to an effective ground ball, per recommendation by Fortenbaugh, (2011)).

For the third 24oz even condition, the numbers in millimeters indicate that the ball was struck 8.65mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball. Next, for the third 16oz donut condition, the numbers in millimeters indicate that the ball was struck 16mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball. Finally, for the second 16oz even condition, the numbers in millimeters indicate that the ball was struck 11.20mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball and the third 16oz even condition indicates the ball was struck 6.60mm below the value of 19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field.

Table 5.

Participant 2 Lowest Point of Bat Trajectory and Location of Contact Relative to Horizontal Midline of the Ball

Condition	Contact at Lowest Point of Bat Trajectory	Location of Contact Relative to Ball Midline (mm)
Baseline	YES	2.36+
Baseline	YES	21.70-
Baseline	YES	30.35+
24oz Power Sleeve	YES	41.50-
24oz Power Sleeve	YES	18.80+
24oz Power Sleeve	YES	6.40+
24oz Even	YES	36.10-
24oz Even	YES	3.80-
24oz Even	YES	21.50-
16oz Donut	YES	23.50-
16oz Donut	YES	5.10-
16oz Donut	YES	12.70+
16oz Even	YES	43.90-
16oz Even	YES	11.20-
16oz Even	YES	13.30+

Note. + And – symbols indicate contact in millimeters above and below the horizontal midline of the ball, respectively.

As seen in Table 5, participant 2 consistently struck the ball at the lowest point in the bats trajectory in the Z axis for all conditions agreeing with Gray (2002) and Tabuchi, Matsuo, and Hashizume, (2007). Furthermore, for the second baseline condition, the numbers in millimeters indicate that the ball was struck 2.70mm above the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and the third baseline condition, the numbers in millimeters

indicate the ball was struck 20.35mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball. Next, for the first 24oz power sleeve condition, the numbers in millimeters indicate that the ball was struck 22.50mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and the second 24oz power sleeve condition, the numbers in millimeters indicate the ball was struck 8.80mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball.

Next, for the first 24oz even condition, the numbers in millimeters indicate that the ball was struck 17.10mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and for the third 24oz even condition, the numbers in millimeters indicate the ball was struck 2.50mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field. Furthermore, for the first 16oz donut condition, the numbers in millimeters indicate that the ball was struck 4.50mm below the value of -19mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and for the third 16oz donut condition, the numbers in millimeters indicate the ball was struck 2.70mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball.

Finally, for the first 16oz even condition, the numbers in millimeters indicate that the ball was struck 24.90mm above the value of -19.00mm proposed by Fortenbaugh, (2011) for an fly ball to center field and for the third 16oz even condition, the numbers in millimeters indicate the ball was struck 3.30mm above the value of 10.00mm proposed by Fortenbaugh, (2011) for an effective ground ball.

Table 6.

Participant 3 Lowest Point of Bat Trajectory and Location of Contact Relative to Horizontal Midline of the Ball

Condition	Contact at Lowest Point of Bat Trajectory	Location of Contact Relative to Ball Midline (mm)
Baseline	YES	6.20+
Baseline	YES	51.80-
Baseline	YES	16.00-
24oz Power Sleeve	YES	1.50+
24oz Power Sleeve	YES	11.50-
24oz Power Sleeve	YES	1.70+
24oz Even	YES	12.10-
24oz Even	YES	41.30-
24oz Even	YES	33.30-
16oz Donut	YES	28.40-
16oz Donut	YES	40.7+
16oz Donut	YES	4.90+
16oz Even	YES	0.15+
16oz Even	YES	25.20-
16oz Even	YES	32.90-

Note. + And – symbols indicate contact in millimeters above and below the horizontal midline of the ball, respectively.

As seen in Table 6, participant 3 consistently struck the ball at the lowest point in the bats trajectory in the Z axis for all conditions agreeing with Gray (2002) and Tabuchi, Matsuo, and Hashizume, (2007). Furthermore, for the second baseline condition, the numbers in millimeters indicate that the ball was struck 32.80mm below the value of -19mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field. Next, for all 24oz power sleeve conditions, the numbers in millimeters dictate that the ball was struck within the range of 29.00mm (19.00mm below the balls horizontal midline for an effective fly ball, as well as 10.00mm above the balls horizontal midline to an effective ground ball, per recommendation by Fortenbaugh, (2011)).

Moreover, for the first 24oz even condition, the numbers in millimeters indicate that the ball was struck within the range of 29.00mm. For the second 24oz even condition, the numbers in millimeters indicate the ball was struck 22.30mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and for the third 24oz even condition, the numbers in millimeters indicate the ball was struck 14.30mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field. Next, for the first 16oz donut condition, the numbers in millimeters indicate that the ball was struck 9.40mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to

center field and for the second 16oz donut condition, the numbers in millimeters indicate the ball was struck 30.70mm above the value of 10mm proposed by Fortenbaugh, (2011) for an effective ground ball.

Finally, for the second 16oz even condition, the numbers in millimeters indicate the ball was struck 6.20mm below the value of -19mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and for the third 16oz even condition, the numbers in millimeters indicate that the ball was struck 13.90mm below the value of -19.00mm proposed by Fortenbaugh, (2011) for an effective fly ball to center field and.

Chapter V

DISCUSSION

Mastering the skill of hitting a baseball is essential for improving individual success and theoretically increasing the likelihood of successfully obtaining a team win. Within the scientific literature, a vast number of studies have been conducted on the baseball swing. These studies describe the basic biomechanical principles of the swing, the use of weighted and underweighted warm-ups prior to stepping into the batter box and the acute effects of dynamically wielding a weighted device.

Within the realm of weighted warm-up devices, various conclusions have been documented showing large inconsistencies in the literature as to which is the most appropriate device to use prior to swinging in a game situation to maximize post warm-up swing velocity. Using data illustrated, as well as attempting to rectify limitations of previous studies, the purpose of this study was to comprehensively investigate the effects of various weighted warm-up devices on post warm-up baseball bat velocity.

Specifically, this study focused on investigating a novel approach of weighting a baseball bat by evenly distributing the weight throughout the entire length of the bat rather than placing weight at a specific location using a donut ring or power sleeve. It was anticipated

that the findings from this study would advance scientific knowledge and support invaluable information for coaches, players and strength and conditioning professionals associated with baseball team sports as they seek to select an appropriate device.

5.1 Velocity

The first task of this study was to investigate the effects of various weighted devices on post warm-up baseball bat velocity. This was done by taking the velocity value of the bat marker located at the most distal end of the barrel of the baseball bat while being dynamically wielded in the positive Y axis toward a baseball resting on a standard batting tee.

5.1.1 Participant 1

The main finding within the results of participant one agrees with previous research conducted by Szymanski et al., (2011), DeRenne, Ho, Hetzler, & Chai, (1992), Montoya et al. (2009), Otsuju, Abe, and Kinoshita, (2002) and Southard and Groomer (2003). These studies stated that two of the most commonly used warm-up devices throughout all levels of play, the 16oz donut ring and 24oz power sleeve, produced slower bat velocities. Slower velocities were observed after warming-up with the donut ring (Fig. 3-4). However, these data disagree with Szymanski et al., (2011), DeRenne, Ho, Hetzler, & Chai, (1992) for the sole reason that an increase in bat

velocity was observed after dynamically wielding the heavier 24oz power sleeve (Fig.1-2 and Table 1).

Observing higher velocities while swinging the heavier bat could possibly be explained by Henneman's size principle of motor unit recruitment. The size principle of motor unit recruitment, first investigated by Elwood Henneman in 1957, then further investigated in numerous later studies, states that the size of the newly recruited motor unit increases with the tension level at which it is recruited, which means that the smallest unit is recruited first and the largest unit last (Henneman, 1974a). In other words, Type I or slow-twitch, low-force, fatigue-resistant muscle fibers are activated before Type II or fast-twitch, high-force, less fatigue-resistant muscle fibers. In this manner, low tension movements can be achieved in finely graded steps while movements requiring high forces, such as the baseball swing that do not require fine control, are accomplished by recruiting the larger motor units (Winter, 2009).

Motor unit recruitment depends on the force and resistance of the movement. With light intensity Type I, slow-twitch, motor units are recruited. When the load is increased, the Type IIa, fast twitch are recruited with the help of the Type I fibers. When the load becomes even greater, the Type IIb/x will be recruited with the help of the Type IIa and Type I motor units. When looking at the percent difference

results for the bats with the additional 16oz weight (Table 1), one could postulate that the size principle wasn't utilized to its fullest potential. It's plausible that only Type I and IIa fibers were recruited which would produce less force applied to the bat resulting in less power and speed of the swing than if the higher force producing Type IIb/x were also recruited. It is possible that by not having a load great enough to elicit the recruitment of those higher force fiber types, a decrease in swing has been observed after dynamically wielding the additional 16oz weighted bats when compared to the additional 24oz weighted bats.

Table 1 also illustrates that the more massive, additional 24oz weighted bats, showed an increase in post warm-up velocity. Again, Henneman's size principle of motor unit recruitment could explain these results. Similar to the 16oz results, Type I and Type IIa motor units may have been recruited with the extra load placed onto the warm-up bat, with the only difference from the 16oz results being the possible recruitment of Type IIb/x motor units which would produce more force applied to the bat thus resulting in a faster swing. In other words, the participants utilized all motor units available to perform the task, unlike the 16oz conditions where only 66% of the available motor units, based upon the three types of motor units available were utilized. Moreover, previous studies have shown that preloading a muscle can

augment force production and motor unit recruitment (Tillin & Bishop, 2009; Kamimura & Takenaka, 2007).

Preloading is defined as the load to which a muscle is subjected before shortening (The American Heritage® Stedman's Medical Dictionary). Kovalski and colleagues, (1995) suggest that preloading the muscle by performing an isometric contraction prior to initiating a concentric muscle action may enhance the ability to generate high tension at the start of the movement or early in the range of motion. Since skeletal muscle fibers do not run the entire length of the muscle, some of the muscle fibers that are active early in the range of motion will not be fully activated unless the muscle is loaded prior to the muscle action (Baechle & Earle, 2008). This preloading may be a result of statically holding the bat in the ready position after swings with additional inertia prior to initiation of the swing for the experimental condition, thus increasing the active state of the muscle and enhancing performance.

Effective force production may be limited in the very early portion of the range of motion, especially in fast movements, but this may be somewhat overcome with a prior isometric contraction (Kumar, 2004). One may postulate that with the additional mass the power sleeve provides, an increased isometric contraction of the triceps may lead to increased number of cross bridge attachments within the

muscle resulting in more work and kinetic energy applied to the bat throughout the swing, possibly resulting in the increased velocity observed with the 24oz device because preloading is important in the development of strength early in the movement especially at high velocities (Baechle & Earle, 2008).

To further explain the increase in post warm-up velocity in the more massive 24oz additional weighted bats, the phenomenon of postactivation potentiation (PAP), which is the focal point of complex training theory, will be explored. PAP is a phenomenon that has gained popularity in the strength training community because it offers a proposed approach for optimizing force and power production above and beyond performance achieved without the use of PAP (Robbins, 2005; Horwath & Kravitz, 2008). The PAP phenomenon can potentially maximize performance of explosive based activities such as weightlifting, sprinting, jumping and throwing activities (French, Kraemer, Cooke, 2003; Hilfiker, Hubner, Lorenz & Marti, 2007).

The fundamental belief encompassing PAP is that preceding heavy loading encourages an increased degree of central nervous system (CNS) stimulation, which results in greater motor unit recruitment and force, which can linger from five-to-thirty minutes (Chiu, Fry, Weiss, et al., 2003; Rixon, Lamont, & Bemden, 2007). An assumption made by strength and conditioning specialists is that

muscles with shorter twitch contraction times show predominance in Type II muscle fibers and exhibit greater force than those muscles with longer twitch contraction times, or Type I fibers (Horwath & Kravitz, 2008). A study conducted by Hamada et al. (2000a) showed that PAP is most effective when Type II fibers are at a greater percentage of the muscles being used. Thus, this phenomenon can be correlated to an increased performance in athletes who rely on a shorter twitch contraction time for optimal athletic performance in spurt activities such as sprinting, jumping, throwing and hitting (Horwath & Kravitz, 2008); further solidifying the postulation that the 24oz weighted bats elicited a greater number of Type II fiber types resulting in an increased swing velocity post warm-up when comparing to the 16oz weighted bats.

There are two theories associated with PAP. The first theory explains the increase in muscle activation at the physiological level with increased phosphorylation of myosin regulatory light chains during a maximum voluntary contraction (MVC). This permits the actin and myosin binding sites to be more responsive to the calcium ions released from the sarcoplasmic reticulum, eliciting a chain of events leading to enhanced force muscle production at the structural level of muscle (Hamada, Sale, & MacDougall 2000). The greater the muscle activation, the greater the duration of calcium ions in the muscle cell environment and the greater the phosphorylation of the myosin light

chain protein (Rixon, Lamont, Bemden, 2007) resulting in faster contraction rates and faster rates of tension development (Chiu, Fry, Weiss, et al. 2003).

Secondly, PAP involves the Hoffmann Reflex (H-Reflex), named after the scientist Paul Hoffmann who first defined it in 1910. The H-reflex is an *excitation* of a spinal reflex elicited by the Group Ia afferent muscle nerves, which are specialized nerves that may augment the action potential to the muscle. The neural circuitry responsible for the H-reflex is primarily characterized by the monosynaptic projection of the group Ia afferents (Misiaszek, 2003) onto the ventral horn of the homonymous motor neurons. The afferent volley then proceeds to the spinal cord leading to a monosynaptic excitation of the target motor neurons and the subsequent activation of the muscle fibers (Misiaszek, 2003).

It is theorized that the PAP intervention enhances the H-reflex, thus increasing the efficiency and rate of the nerve impulses to the muscle (Hodgson, Docherty, Robbins, 2005), which may also explain the increase in swing velocity in the 24oz weighted bat conditions (Table 1, Fig. 1-2). However, the contrary may hold true for spinal reflex for the 16oz bat conditions (Table 1, Fig 3-4) where PAP may not have been observed because of a spinal *inhibition* via the descending supraspinal pathways of the monosynaptic excitatory

pathway, or Group 1a afferent muscle nerves and the disynaptic reciprocal inhibitory pathway, or muscles on one side relax for the contraction of the muscle on the other side (Kjaer, Krogsgaard, Magnusson, et al., 2008), resulting in a coactivation of the agonist and antagonist.

Coactivation is the mechanical effect of making a joint more stiff and difficult to perturb which contradicts the notion of reciprocal activation. Reciprocal activation is defined as the simultaneous activation of muscles with a mechanical action on a joint (agonist) and inhibition of muscles with the opposite mechanical action (antagonists) (Binder & Hirokawa, 2009). One may postulate that during the 16oz conditions, the increase in muscle and joint stiffness may have resulted from direct activation from the CNS with the cerebellum playing an important role in switching from reciprocal activation to coactivation (Kjaer, Krogsgaard, Magnusson, et al., 2008). Thus, possibly decreasing the speed of the swing when compared to the 24oz conditions where PAP was predominate due to the excitation of the Group Ia afferent muscle nerves enhancing the H-reflex, rather than an inhibition during the 16oz swings causing a coactivation resulting in a slower swing.

Kauffman and Greenisen, (1973) stated the magnitude of the biceps brachii involvement, after the use of a weighted bat, could

nullify the advantage of additional involvement of the triceps brachii motor unit. Being that there was an increase in post warm-up velocity after dynamically wielding the more massive 24oz bat, one could postulate that there is a threshold switching from coactivation to PAP. It is possible that the load was too light in the 16oz conditions resulting in excluding the higher force producing Type IIb/x fiber types and exhibiting an inhibition of Group 1a afferents, thus not providing an appropriate environment to exhibit a PAP effect. However, once the load was increased, the appropriate fiber types were recruited, and excitation of the Group 1a afferents occurred providing an appropriate environment to exhibit a PAP.

5.1.2. Participant 2

With regards to fiber type and PAP, similar results were observed for participant 2. Although significant differences were not observed an increase in velocity was detected. The power sleeve (Fig 5.), donut (Fig 7.) and the 16oz evenly distributed bat (Fig. 8) showed an increase in velocity, leading to the postulation of the results for participant 1, of an appropriate environment to induce a PAP and a decrease in coactivation to increase the swing velocity. Furthermore, although not measured in this study, participant 2 possessed greater lean body mass which was visually observed from a larger cross sectional area of the upper extremities when comparing to the other

two participants. This larger, visible amount of lean body mass may have resulted in the predominant fiber type being Type II fast twitch fibers, thus further enhancing the environment to exhibit a PAP effect and excitation of the H-reflex to increase swing velocity, however, a decrease in velocity was observed for the 24oz evenly distributed bat (Fig. 6).

High levels of resistance training could have benefits, such as possibly increasing the speed of the swing via conversion (Type IIa to Type IIb/x) and subsequent increased recruitment of those fast twitch motor units (or neural adaptations such as increased reflex potentiation) (Behm, 1995); however, the decrease in velocity may have been a result of the participant not fully complying with the studies explicit instructions to refrain from physical activity prior to testing which could have fatigued the muscles prior to testing.

Muscular fatigue is defined as the acute impairment of performance due to physical activity (Enoka, 2008). Fatigue should not be confused with muscular weakness, but rather understood in the context of the activity related impairment of physiological mechanisms that reduce muscular force (Enoka, 2008), more specifically, the reduction of swing speed. Within the last 100 years, scientists have established that fatigue is not caused by the deficiency of a single mechanism, but rather several mechanisms. Staying within the realm

of the H-reflex associated with PAP and coactivation, an explanation for the decrease in velocity by participant 2 is warranted.

Resistance training may modify the coactivation response. In study conducted by Behm, (1995) trained individuals had statistically insignificant lesser coactivation prior to fatigue but significantly greater coactivation following fatigue. Behm, (1995) postulated that the greater coactivation following fatigue may be related to the finding that trained individuals also had a greater muscle activation and it's possible that supraspinal neural drive following fatigue results in more diffusion of the signals to the antagonist, which may have played a role in decreasing the speed of the swing.

Furthermore, motor neuron excitability is frequently estimated using the H- reflex (Gardiner, 2011) which is a technique used to stimulate the muscles nerve with electrical stimulation of a duration and intensity that excited the Group Ia afferents. The amplitude of the muscle response that follows the stimulation at monosynaptic latency is used as an estimate of the excitability of the motor neuron pool of the muscle and has been used to estimate the changes in the motor neuron excitation with fatigue (Gardiner, 2011). Following a sustained effort, performed maximally to fatigue, H-reflex amplitude decreases or is inhibited signifying a decline in motor neuron excitability which contradicts the excitation of the H-reflex observed during a PAP effect.

Garland and McComas (1990) demonstrated a 50% decrease of the H-reflex amplitude after stimulating the soleus muscle at 15Hz for 10 minutes under ischemic conditions. Duchateau and Hainaut (1993) also found decreased H-reflex amplitude after both MVC to fatigue and electrical stimulation in the adductor pollicis muscle. McKay and colleagues (1995) also reported a decrease in H-reflex amplitude immediately following MVC of the ankle dorsiflexors, thus the excitability of the motor neuron pool decreases with fatigue of the muscle during a maximal effort (Gardiner, 2011).

These findings support that at least part of the decrease in the H-reflex in response to maximal effort is due to decreased excitatory or increased inhibitory influence emanating from the fatigued muscle itself (Gardiner, 2011), thus possibly slowing the swing velocity, rather than increasing the swing speed when the H-reflex is enhanced or excited which was possibly witnessed for participant 1 (Fig 1-2). Withdrawal of facilitation to the motor neuron pool due to a depression of afferent feedback appears to be the more dominant mechanism responsible for the decline in H-reflex size during fatigue (Enoka et al., 2011).

5.1.3. Participant 3

Much like the previous participants, participant 3 showed increases in velocity. Increases were observed for the 24oz evenly distributed (Fig. 10), 16oz donut (Fig.11) and 16oz evenly distributed

conditions (Fig.12). Possible reasons for the increase in velocity under these three conditions may be due to the excitation of the H-reflex, decrease of coactivation of the antagonist and agonist muscles, as well as a proper environment to exhibit a PAP, as was previously mentioned. However, a decrease in velocity was observed after dynamically wielding the 24oz power sleeve. A slightly different approach, explaining the moment of inertia (MOI), will be utilized to possibly explain this decrease which may also be applicable to previous participants decrease in velocity.

MOI is defined as the angular equivalent of inertia (mass) and represents a measure of the resistance that an object offers to a change in its motion about an axis (Enoka, 2008). Being that the axis of rotation is located near the hands when the participants is holding the bat, moment of inertia is increased as the mass is located farther away from the axis of rotation because MOI is not only a function of mass, but more importantly mass distribution. In fact, Fleisig, Zheng, Stodden, & Andrews (2002) stated that swing velocity had a stronger relationship with bat MOI than bat mass because it is possible to have bats with the same mass but varying MOI depending upon the location of the mass.

DeRenne et al., (1992) reported that swing velocity is reduced following a warm-up with a bat weighing more than $\pm 10\%$ of the

standard bat weight (30oz). They theorized that when bat weight was augmented by more than 10%, there may be changes in hitting mechanics that would explain the reduction in swing velocity. Southard and Groomer, (2003) stated, with the use of dynamic systems terminology, that coordination is reorganized when the bat's MOI is scaled to a critical factor. A clue regarding the critical value required to change the swing pattern may lie in the findings of DeRenne et al., (1992) with decreases in velocity occurring when the device to be dynamically wielded exceeds the $\pm 10\%$ range.

As one can observe in the results, participant 3 may have been well within his critical factor to increase velocity (Fig. 10-12, Table 3), however, when the critical factor was above what the participant was able to handle, a decrease in velocity was observed with the more massive 24oz power sleeve (Fig. 9). This may lead to an inflation of the critical factor for this participant. All devices utilized by participant 3 were above the $\pm 10\%$ threshold which DeRenne et al., (1992) suggests, however increases in velocity were observed (Fig 10-12, Table 3). With the use of the evenly distributed 24oz bat, which had the same mass but different MOI, there was an increase in velocity which contradicts the results of the 24oz power sleeve (Fig. 9). This finding supports the results by Fleisig, Zheng, Stodden, & Andrews (2002), in that, MOI has a stronger relationship with swing velocity than overall

bat mass and by manipulating, or decreasing, the MOI while still weighting the bat the critical factor may be increased above the $\pm 10\%$ range providing an appropriate device to increase post warm-up velocity.

5.2. Trajectory for All Participants

The second task of this study was to investigate the effects of various weighted devices on post warm-up baseball bat trajectory. This was done by taking the inverse tangent of the velocity value of the marker located at the end of the barrel of the bat in the Z axis divided by the velocity value of the bat marker in the Y axis multiplied by 57.3 to convert from radians into degrees.

Figures 13-24 illustrate that there were no significant differences in post warm-up trajectory after using any of the weighted devices. One can clarify these results from a myriad of theoretical perspectives. Southard and Groomer, (2003) stated that when hitters swing a bat with a different MOI, they may select a different motor program or reparametrize an existing motor program based upon the information gained prior to or during the swing. However, the use of the dynamical systems theory (DST) will be utilized in order to interpret the data.

Advocates of the DST explain this theory from the perspective of nonlinear dynamics; which means that behavioral changes over time do not follow a continuous, linear progression, but make sudden abrupt

changes (Magill, & Anderson, 2007). A prime example of a dynamic, complex system which makes abrupt changes is a hurricane. A hurricane does not follow a linear progression, however, when environmental conditions present themselves in an appropriate manner, a hurricane emerges, thus representing nonlinear behavior.

A focal point of the DST is the concept of stability and attractors. Stability refers to the behavioral steady state of a system and incorporates the notion of variability by noting that when a system is slightly perturbed, it will spontaneously return to a stable state (Magill, & Anderson, 2007). For example, Kelso (1984) and Kelso and Scholz, (1985) had participants rhythmically move their right and left index finger at a specified rate of speed in an antiphase relationship. The researchers observed behavioral stability when the fingers were in antiphase and in-phase relationships with each other. These two states represent two coordinated movement patterns; however as finger speed increased a phase transition occurred during which instability characterized the behavioral pattern (Magill, & Anderson, 2007). This instability was sustained until finger speed reached a point at which a new stable state spontaneously occurred. With regards to Figures 13-24, the participant's motor system may have been slightly perturbed with the increase in MOI, but then spontaneously returned back to a

stable state where the participants were able to successfully make contact with the baseball resting on the batting tee.

Attractors, or attractor states, are defined as stable behavioral steady states. They are the preferred behavioral states and represent stable regions of operation around which behavior typically occurs when the system is allowed to operate within its preferred manner (Magill, & Anderson, 2007). Also, attractor states are not only stable states characterized by minimal behavioral variability, but also optimally energy efficient states (Magill, & Anderson, 2007); this means that when a person is utilizing a preferred coordination pattern, that person uses less energy than her or she would be moving at a non-preferred rate (Magill, & Anderson, 2007). Being that there was no significant differences (Fig.13-24), one may postulate that the performer settles into an attractor state, after a slight perturbation with the increased MOI, which is the preferred strategy to make contact with the ball based upon information gathered from the environment. Also, maximizing the energy transfer from the more distal regions (legs) to the end effector (bat), thus maximizing energy efficiency resulting in a more accurate and fluid movement.

Lastly, control parameters, which represent the variable that when increased or decreased will influence the stability and character of the order parameter (Magill, & Anderson, 2007). This was exploited

in the Kelso experiments briefly explained above. Speed acted as the control parameter and as the movement frequency was increased the phase relationship underwent distinct changes. In-phase relationship was maintained through several frequencies (speeds), but then began to destabilize as frequency continues to increase (Magill, & Anderson, 2007). As frequencies increased further, a critical frequency at which a new antiphase relationship emerged and became stable.

Southard and Groomer, (2003) stated, from a DST viewpoint, that considering the bat as an extension of the performer, an increase in the bats MOI leads to a reorganization of the movement pattern. The authors further stated that coordination is reorganized when the bats MOI, serving as the control parameter, is scaled to a critical value and the recommendation set by DeRenne et al., (1992) of $\pm 10\%$ of the standard weight bat may be a clue regarding the critical value required to change the swing pattern (Southard and Groomer, 2003).

Again, being that there were no significant differences (Fig.13-24), the performer may have not approached that critical value for an emergence of an altered movement pattern. Thus, the swing pattern were perturbed slightly with the increase in MOI relative to the 30oz bat, then settle back into an attractor state where the system used the strategy to maximize energy efficiency and was allowed to move in its preferred manner. One can postulate that we have extended the

critical value beyond $\pm 10\%$ range. With the use of the weighted bats, the results dictate that we may be able to load the bat with more weight, thus exceeding DeRenne et al., (1992) recommendations, while not affecting the preferred state of the athlete's movement pattern.

5.3 Location of Ball Contact with Respect to Horizontal Midline of the Ball for All Participants

Anecdotally, Ted Williams, arguably the greatest hitter of all time, recommended a slight upswing of the bat because the trajectory of the swing matches the trajectory of the pitched ball. This notion was supported scientifically by Williams and Underwood (1986) who stated that when attempting to produce maximum range of the baseball post-impact, a slight upswing seems to be the best strategy. Furthermore, Sawicki et al. (2003) stated the optimal strategy to impose for maximal range of the ball post-impact is to swing the bat at an upward angle of $\sim 9^\circ$ which suggests the bat angle matching the angle of the pitched ball to hit a home run. Moreover, Messier and Owen (1984) found in female softball athletes that there is a slight downward velocity of the bat, then an increase in the upward velocity at impact for all trials.

The results from this study (Table 4-6) contradict the studies reported above; however, they support the findings of Gray (2002) and Tabuchi, Matsuo and Hashizume (2007). Gray (2002) utilized the

lowest point of the bat head as a criterion to identify impact, in other words, the bat head was at its minimum in its trajectory during the swing. Tabuchi et al., (2007) stated that it is desirable that impact occurs when the bat head is at its lowest point in the trajectory and at peak speed because when hitting at the lowest point of trajectory, vertical displacement of the bat head is minimized (Tabuchi et al., 2007). This means that small temporal errors do not result in large spatial errors around the lowest position in the bats trajectory.

Fortenbaugh, (2011) proposed that 'swinging the bat 50 millimeters below the ball's center would result in a ball fouled high and straight back over the catcher's head and out of play, swinging the bat 25 millimeters below the ball would result in a routine fly-out, but that swinging the bat 19 millimeters below the ball's center would maximize the ball's flight distance, partially by creating backspin to further propel the ball.' Fortenbaugh, (2011) further stated that 'an effective ground ball hit should not make contact more than 10 millimeters above the ball's center.' One can postulate that there is an optimal range for contacting the ball, relative to the horizontal midline of the ball, of 29mm (19mm below and 10mm above the midline). When hitting at the lowest point of the bats trajectory, these errors may be minimized.

Hitters have an advantage when they hit the ball at the instant of peak speed. If hitters want to maximize the range of the batted ball,

impact should occur at the time of peak speed of the bat head, which will provide a higher probability of hitting the pitch (Tabuchi et al., 2007). However, this strategy may impose complicated processing time on the hitters, because a new motor pattern may emerge on a pitch by pitch basis (Tabuchi et al., 2007).

Although maximum velocity was observed at the point of impact (Table 1-3), it was slightly lower than a comparable cohort of participants (Division 3) utilized by Reyes and Dolny, (2009) with average velocity values of 64 miles per hour. One can postulate that the participants in this study did not use the strategy of maximizing velocity at the instant of impact, but rather imposed a strategy of minimal error at contact via the least vertical displacement, or lowest point in the bats trajectory, when hitting a stationary ball to remain within the range of 29mm for optimal ball contact for an effective fly or groundball. Using dynamical systems terminology to explain this notion, the participant may have settled into an attractor state which was the preferred movement pattern and the most energy efficient given the information gathered by the performer when hitting a stationary ball off of the tee. Also, it seems that the control parameter, MOI, was not scaled to a critical value to perturb the hitters preferred strategy of contact at the lowest point in the bats trajectory.

Chapter VI

SUMMARY AND CONCLUSION

Much like Reyes and Dolny, (2009), this study found no significant differences in velocity, however increases in post warm-up velocity was observed which cannot go unrecognized. For every 1 mile per hour increase in swing velocity, a distance of 8 feet of flight time is added to the ball post impact which may result in a routine fly ball exceeding the distance of the fence resulting in a home run. This may directly affect the outcome of the game while at the same time increasing the performance of the participant (slugging percentage, batting average, etc.).

When comparing the results of the current study to those of DeRenne et al., (1992) which utilized high school participants with similar conditions and the same procedures, level of play seems to play a vital role. Participants possessing greater experience, better mechanics and increased strength showed a greater increase in post warm-up velocity. The older, stronger, more experienced participants may be able to overcome the inertia added to the bat thus resulting in a greater post warm-up effect which contradicts most studies investigating post warm-up velocity immediately following a weighted intervention. It seems that as level of play increases, the critical value of $\pm 10\%$ of the standard bat weight proposed by DeRenne et al.,

(1992) and further substantiated by Southard and Groomer (2003) is also increased resulting in no detrimental effects to swing velocity and trajectory.

With the increase of the critical value, the bat may be loaded with more weight to allow the participant to take advantage of the PAP effect to the muscles while not severely affecting the swing pattern or sacrificing velocity when swinging during a game situation. This allows the participant more freedom to select an appropriate device to maximize post warm-up velocity. Based upon the results of this study, division two athletes can choose any one of the warm-up devices investigated because no deleterious effects were observed.

Future Recommendations

Within this study, claims were made to refute PAP with the use of fiber typing, reciprocal activation and inhibition, as well as coactivation. EMG is a valuable tool to measure these phenomena which were not used in the present study, being that we were solely interested in the subsequent velocity of the baseball bat following a specific weight bat intervention. In future studies dealing with velocity, it will be advantageous to utilize EMG to scientifically evaluate the intricacies of a muscle firing pattern to substantiate the claims of coactivation and reciprocal inhibition/activation via onset/offset reports and peak activation of the muscles of interest. By utilizing EMG in

subsequent studies, it will answer many questions raised by this study of the muscular involvement during the swing.

Furthermore, attractor states were mentioned throughout the discussion to explain the consistency of the swing at contact. In future studies, it may be advantageous to rearrange, in a randomized manner, the location of the baseball resting on the tee. Correlation statistics will also serve as a valuable tool to strengthen the claims of the participants settling into an attractor state if correlation coefficients emerge as significant. With this additional information, the researcher can obtain more concrete evidence that the attractor state of the participants remains with varying locations of the ball. If the attractor state remains, one can draw scientific conclusions that the participant consistently contacts the ball within the recommended range (19mm below and 10mm above the horizontal midline of the ball) and regardless of the location of the ball at contact and the perturbation to the system. Not only will this add more information of the attractor state of the participants, but increase the sports specificity of the study because the baseball, in a game time situation, rarely travels belt high and down the middle of the plate on a consistent basis.

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Appendix A

Recruitment Flyer

Are you a position player for the University Baseball Team??

Volunteer to Get Involved in Research!!!

Title: Effects of Various Warm-Up Devices on Bat Velocity and Trajectory in Collegiate Baseball Players

Purpose: The purpose of this project is to examine the effects of various weighted warm-up devices on baseball bat velocity and trajectory of collegiate baseball players.

Procedures: Baseline bat velocity measurement with 30oz baseball bat to serve as a control. Next, a general warm-up of stretching for 1 minute with a weighted device, followed by a specific warm-up of swinging a weighted device 4 times as fast as possible. Next, the participant will swing a 30oz bat 2 times in a way that is comfortable followed by three swings with a standard bat for ball contact off of a baseball tee. All devices (4) will be used by all participants and the same warm-up procedure will be conducted for all participants for each session (5). 39 reflective markers will be secured to specific locations on the subjects head, trunk, upper extremities and lower extremities via Velcro (clothing covered locations) and 3-M two-way tape (bare skin locations). Additionally, surface EMG sensors will be attached bilaterally (left and right) to the participant's latissimus dorsi, posterior deltoid, triceps and biceps. Specific locations of the sensors will be thoroughly cleaned with an alcohol pad and an over the counter exfoliating scrub to rid the locations of body oils which ensures maximum adhesion to the skin.

Who: Male university position baseball players at least 18 years of age. Participants are volunteers and can withdraw participation at any time without penalty. Anonymity and confidentiality is of the utmost importance. Data will be protected and only available to the primary researcher. All data will be secured and identifying marks will not be used in publication of any form.

Time: Participants are asked to come to the lab a total of 5 times for approximately 1 hour

When: Spring 2015 semester

Where: Koehler Field House Biomechanics laboratory

Contact: Jordan L. Cola

Seton Hall University
Doctoral Candidate
Department of Graduate Programs in Health Sciences
School of Health and Medical Sciences
570-527-2762
cola_95@hotmail.com

This research is conducted under the direction of Dr. Genevieve Zipp, and Dr. Fortunato Battaglia, Department of Health Sciences, Seton Hall University and Dr. Gavin Moir, East Stroudsburg University Department of Exercise Science. This study has been reviewed and approved by the Seton Hall and East Stroudsburg University Review Boards.

Appendix B

Informed Consent



Informed Consent Form

Seton Hall University

‘Effects of Various Warm-Up Devices on Bat Velocity and Trajectory in Collegiate Baseball Players’

Researcher’s Affiliation

Jordan L. Cola, who is a Graduate Student at Seton Hall University in the department of Interprofessional Health Sciences and Health Administration in the School of Health and Medical Sciences, has requested the subject’s participation in a research study at East Stroudsburg University. The title of the research is: Effects of Various Warm-Up Devices on Bat Velocity and Trajectory in Collegiate Baseball Players.

Research Purpose

The subject has been informed that the purpose of the research is to examine the effects of various weighted warm-up devices on standard baseball bat velocity and trajectory of collegiate baseball players. Secondly, to examine subjective judgment scales for swing speed and baseball bat heaviness to investigate the effect on swing velocity of subsequent batting after swinging a weighted bat. The subject understands that if he chooses to participate in this study, the subject will be asked to report to the biomechanics laboratory during a scheduled time, over a 5 day period for approximately 45 minutes for each session.

Research Procedures

The subject has been informed as part of the research protocol he will be asked to come to the biomechanics laboratory once to fill out health history and Par-Q forms, as well as an informed consent. Following the signing of documents, anthropometric measurements will be taken by the principle investigator using anthropometric calipers and a tape measure to obtain information for the 3-D motion analysis system. On the second meeting a familiarization session will take place where the participants will be asked to wear neoprene (spandex) baseball sliding shorts and a neoprene shirt for the familiarization and each subsequent visit to the biomechanics laboratory. At this time, 39 reflective markers will be secured to specific locations on the subjects head, trunk, upper extremities and lower extremities. On the locations which are covered by clothing, the markers will be attached via Velcro; for the parts of the body which are exposed (knees, ankles, wrists, fingers), 3-M two-way tape will be used to secure the marker to the anatomical landmark. Furthermore, bilateral (left and right side) surface electromyography sensors will be secured to the latissimus dorsi, posterior deltoid, triceps and biceps.

Specific locations of sEMG sensors will be thoroughly cleaned with an alcohol pad and an over the counter exfoliating scrub to rid the location of body oils to allow the sensor to be firmly attached to the skin. The reason for the familiarization will be to allow the participants become accustomed to having external sensors for surface Electromyography (sEMG) and retro-reflective markers attached to the body while performing a typical swinging motion that is considered a normal facet of a structured baseball practice throughout the season

Following the familiarization and once the reflective markers are secure, the participant will be asked to take part in a standardized warm-up protocol before using any of the various weighted devices. The standardized warm-up protocol will mimic what is done during a normal University baseball practice with a general warm-up of jogging and specific baseball stretches (arm circles, upper and lower body stretches etc.). Following the standardized warm-up, the weighted baseball bat warm-up will take place. This warm-up will consist of various weighted baseball bats including overhead and behind the back stretching while using one of the weighted bats for exactly one minute. The participant will then be instructed to swing one of the devices four times as fast as possible in a typical batting motion. Immediately following the warm-up swing with one of the weighted devices, the participant will be instructed to pick up a standard game time bat typically used in competition and swing it two times in a way which is comfortable. Following the swinging of the game bat, the experimental trial will begin. The experimental trial will consist of swinging a standard game bat three consecutive times with twenty seconds between each swing while making contact with a baseball resting on a standard batting tee. The location of the ball will be located in an area which will be consistent with a fastball down the middle of home plate. The height of the baseball will be belt high. This location is ideal for maximum contact with the ball. The testing order of weighted bats will be randomized for each visit and counterbalanced so the participant will repeat the protocol until all variations of the overweight bat will be experienced.

Voluntary Nature

The subject understands that his participation in this study is of a voluntary nature. The subject will not be compensated monetarily for their participation. The subject also understands that at any time during the course of the research he can withdraw from participation at any time, with no repercussions from the parties and their affiliates involved with this study.

Anonymity

The subject understands that the results of the research study may be published but the subjects name or identity will not be revealed. Additionally, there will be no identifying marks which could link the subject to any individual data.

Confidentiality of Records

In order to maintain confidentiality of the subject's records, Jordan L. Cola will provide the subject with a subject code and that will be the only way data will be identified. Additionally, the subject understands that records will be kept secure in a locked file cabinet in Jordan L. Cola's home office. At no point will any data with identifying marks become available to the public.

Records

The subject understands that Jordan L. Cola and the head of the biomechanics laboratory, Dr. Gavin Moir, will be the only people with access to any confidential records. Dr. Gavin Moir will have a password protected USB drive serving as a backup source of information in the event of electronic failure of the password protected USB drive possessed by Jordan L. Cola. Dr. Moir will not know the password to this jump drive, for it will only serve as a redundant USB drive. The subject understands their records will be kept for a period of three years after which time they will be destroyed.

Risks or Discomforts

The subject understands that there are minimal foreseeable risks or discomforts if the subject agrees to participate in the study. The possible risks include mild muscle soreness or other minor musculoskeletal injuries during or after the weighted bat swing protocol. Also, minor skin irritation may arise from the exfoliating scrub while preparing the skin surface to the application of sEMG sensors. The subject also understands that immediate medical attention is available through the East Stroudsburg University Health Center or at the local Hospital located adjacent to the campus. Furthermore, the athletic training laboratory which is always staffed by a certified athletic trainer is next door to the biomechanics laboratory. The subject understands if they have further questions about possible risks or discomforts they can contact Jordan L. Cola at any time for further explanation.

Direct Benefits

The subject understands that the possible benefits of their participation in this research may include gaining some knowledge into the research process and more importantly the possibility of increasing post warm-up bat velocity which would directly benefit athletic performance while playing in a game situation.

Monetary Compensation

The subject has been informed that he will not be compensated monetarily in for participation.

Contact Information

The subject has been informed that any questions the subject may have concerning the research study or participation in it, before or after consent, will be answered by the principle investigator Jordan L. Cola, Graduate programs in Interprofessional Health Sciences and Health Administration, School of Health and Medical Sciences; 400 South Orange Avenue, South Orange NJ 07079 or at (973) 275-2076. Additional information can be

obtained from Dr. Genevieve Pinto Zipp, Seton Hall University, Graduate programs in Health Sciences, School of Health and Medical Sciences; 400 South Orange Avenue, South Orange NJ 07079 or at 973-275-2457. If the subject has any questions about rights as a subject/ participant in this research, or if the subject feels they have been placed at risk, the subject can contact the Director of the Institutional Review Board: Dr. Mary Ruzicka at 973-313-6314, Seton Hall University. 400 South Orange Avenue, South Orange NJ 07079.

Signatures

THE PARTICIPANT IS MAKING AN INFORMED DECISION WHETHER OR NOT TO PARTICIPATE. THE PARTICIPANT UNDERSTANDS HE IS FREE TO WITHDRAW FROM THE STUDY AT ANY TIME WITH NO REPERCUSSIONS. A copy of this signed and dated consent form will be given to the subject.

Subject's Signature _____ **Date** _____

Appendix C

Health History Injury Form

Health Status
Musculoskeletal Injuries (Within last 8 months)
Check all that apply and explain injuries

Joint	No Injury	Injury (Explain)
Neck		
Shoulder		
Back		
Hip		
Knee		
Ankle		
Foot		
Elbow		
Wrist		
Fingers		

Accepted_____

NOT Accepted_____

Subject Code _____ Date _____

ATC Signature _____ Date _____

P.I. Signature _____

Date _____

Appendix D

IRB Approval East Stroudsburg University

200 Prospect Street
East Stroudsburg, PA
18301-2999



East Stroudsburg University Institutional Review Board
Human Research Review
Protocol # **ESU-IRB-066-1314**

Date: **June 27, 2014**
To: **Jordan Cola and Gavin Moir**
From: **Shala E. Davis, Ph.D., IRB Chair**
Proposal Title: **"Effects of Various Warm-up Devices on Baseball Bat Velocity and Trajectory in Collegiate Baseball"**

Review Requested: Exempted Expedited **X** Full Review
Review Approved: Exempted Expedited **X** Full Review
FULL RESEARCH

- Your full review research proposal has been approved by the University IRB (12 months). Please provide the University IRB a copy of your Final Report at the completion of your research.
- Your full review research proposal has been approved with recommendations by the University IRB. Please review recommendations provided by the reviewers and **submit necessary documentation for full approval.**
- Your full review research proposal has not been approved by the University IRB. Please review recommendations provided by the reviewers and resubmit.

EXEMPTED RESEARCH

- Your exempted review research proposal has been approved by the University IRB (12 months). Please provide the University IRB a copy of your Final Report at the completion of your research.
- Your exempted review research proposal has been approved with recommendations by the University IRB. Please review recommendations provided by the reviewers and **submit necessary documentation for full approval.**
- Your exempted review research proposal has not been approved by the University IRB. Please review recommendations provided by the reviewers and resubmit, if appropriate.

EXPEDITED RESEARCH

- Your expedited review research proposal has been approved by the University IRB (12 months). Please provide the University IRB a copy of your Final Report at the completion of your research.
- Your expedited review research proposal has been approved with recommendations by the University IRB. Please review recommendations provided by the reviewers and **submit necessary documentation for full approval.**
- Your expedited review research proposal has not been approved by the University IRB. Please review recommendations provided by the reviewers and resubmit, if appropriate.

Please revise or submit the following:

Appendix E

IRB Approval Seton Hall University



OFFICE OF INSTITUTIONAL
REVIEW BOARD
SETON HALL UNIVERSITY

December 15, 2014

Jordan Cola
11 Lewis Street
Minersville, PA 17954

Dear Mr. Cola,

The Seton Hall University Institutional Review Board has reviewed the information you have submitted addressing the concerns for your proposal entitled "Effects of Various Warm-Up Devices on Baseball Bat Velocity and Trajectory in Collegiate Baseball Players." Your research protocol is hereby approved as revised under full review.

Enclosed for your records are the signed Request for Approval form, the stamped original Consent Form, and the stamped Recruitment Flyer. Make copies only of these stamped documents.

The Institutional Review Board approval of your research is valid for a one-year period from the date of this letter. During this time, any changes to the research protocol must be reviewed and approved by the IRB prior to their implementation.

According to federal regulations, continuing review of already approved research is mandated to take place at least 12 months after this initial approval. You will receive communication from the IRB Office for this several months before the anniversary date of your initial approval.

Thank you for your cooperation.

In harmony with federal regulations, none of the investigators or research staff involved in the study took part in the final discussion and the vote.

Sincerely,



Mary F. Ruzicka, Ph.D.
Professor
Director, Institutional Review Board

cc: Dr. Genevieve Pinto-Zipp

Presidents Hall • 400 South Orange Avenue • South Orange, New Jersey 07079-2641 • Tel: 973.313.6314 • Fax: 973.275.2361

A HOME FOR THE MIND, THE HEART AND THE SPIRIT

Appendix F

Physical Activity Readiness Questionnaire (PAR-Q)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
<input type="checkbox"/>	<input type="checkbox"/>	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
<input type="checkbox"/>	<input type="checkbox"/>	2. Do you feel pain in your chest when you do physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	3. In the past month, have you had chest pain when you were not doing physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
<input type="checkbox"/>	<input type="checkbox"/>	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
<input type="checkbox"/>	<input type="checkbox"/>	7. Do you know of <u>any other reason</u> why you should not do physical activity?

If
you
answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.



DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT
or GUARDIAN (for participants under the age of majority) _____

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



© Canadian Society for Exercise Physiology www.csep.ca/forms

Appendix G

Physical Activity Readiness Questionnaire (PAR-Q) Approval Form



Canadian Society for Exercise Physiology,
#370 18 Louisa St Ottawa ON K1R 6Y6
1 877 651 3755 info@csep.ca

Date: March 16, 2016

COPYRIGHT PERMISSIONS SUMMARY

Name Author/Publisher	Jordan Cola
Address	5-540 Main Street Stroudsburg PA, 18360
Title of Publication	The Effects of Various Warm-Up Devices on Bat Velocity and Trajectory in Collegiate Baseball Players
Publication Type	<input type="checkbox"/> Electronic use (eBook, website, app) <input type="checkbox"/> Print use <input type="checkbox"/> College/University Coursepak: <input type="checkbox"/> Electronic <input type="checkbox"/> Print <input checked="" type="checkbox"/> Other (describe): Dissertation

Details of CSEP Work(s) Used	Description	Subject to Fees Yes/No	Acknowledgement Line
PAR-Q	Physical Activity Readiness Questionnaire (PAR-Q) Copyright 2002	<input type="checkbox"/> YES <input checked="" type="checkbox"/> NO	2
		<input type="checkbox"/> YES <input type="checkbox"/> NO	-
		<input type="checkbox"/> YES <input type="checkbox"/> NO	-
		<input type="checkbox"/> YES <input type="checkbox"/> NO	-
		<input type="checkbox"/> YES <input type="checkbox"/> NO	-
		<input type="checkbox"/> YES <input type="checkbox"/> NO	-

SUMMARY: Permission granted for use of the PAR-Q

NOTES: As per e-mail request by Jordan Cola
February 15th, 2016.

Invoice # N/A

LEGEND: Acknowledgement Lines

- Source: *Canadian Physical Activity, Fitness & Lifestyle Approach: CSEP-Health & Fitness Program's Appraisal and Counselling Strategy*, 3rd edition, © 2003. Reprinted with permission from the Canadian Society for Exercise Physiology.
- Source: Physical Activity Readiness Questionnaire (PAR-Q) © 2002. Used with permission from the Canadian Society for Exercise Physiology www.csep.ca.
- Source: Canadian Physical Activity Guidelines, © 2011. Used with permission from the Canadian Society for Exercise Physiology, www.csep.ca/guidelines.
- Source: Canadian Sedentary Behaviour Guidelines for Children and Youth, © 2011. Used with permission from the Canadian Society for Exercise Physiology, www.csep.ca/guidelines.
- Acknowledgement line not required