ENHANCED SENSORIMOTOR KINEMATICS OF THE BASEBALL SWING IN ELITE BATTERS DURING A KNOWN PITCH TYPE

by

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The interceptive task of hitting a baseball requires temporal and spatial precision through effective pitch tracking strategies and swing mechanics to achieve success. Overall, these factors dictate the quality of the contact and therefore successful performance of the task. The permitted response time for a batter to visually react and analyze the trajectory of the ball, produce the movement of the swing, and create quality contact is a fraction of a second. In this study, temporal analysis and the measurement of sensorimotor factors indicative of skill was completed in different pitch conditions to understand the changes that occur as a result of whether the pitch type is known. Additionally, correlations between sensory and motor kinematics of the baseball swing were examined. Sixteen participants were divided in to two subgroups based on their highest level of baseball experience. The sub-elite group consisted of individuals whose highest level of playing experience was at the high school varsity level, while the elite group included collegiate players up to the NCAA Division I level. Utilizing live pitching in an indoor batting facility, a 12-camera motion capture system, and eye tracking glasses, each subject completed 20 totals trials across a known fastball, known curveball, and unknown mixed conditions. For the fastball trials only, pelvis rotation and angular velocities along with the load phase, load-release difference, land phase, launch phase, and swing duration were measured and represent the motor variables while head and eye rotation and average angular velocity represent the sensory variables measured. Results demonstrated significant differences in head rotation, average head angular velocity, pelvis rotation, and load-release difference between the known and unknown conditions, significant differences in the load phase, land phase, and total swing durations, as well as the load-release difference between elite and sub-elite batters, along with a significant interaction between skill level and pelvis rotation for pitch condition ($p < 0.05$). Additionally, relationships were found between eye and head rotation with pelvis and swing phase kinematics for both the elite and sub-elite groups ($p < 0.05$). Overall, understanding the kinematic differences between pitch conditions and skill level can lead to more effective training strategies to enhance performance.

Enhanced Sensorimotor Kinematics of the Baseball Swing in Elite Batters during a Known Pitch Type

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Chapter I: Introduction

The interceptive task of hitting a baseball is widely regarded as one of the most challenging in all of sports. It is a skill that requires a batter to produce square contact between two round objects, the bat and the ball, which are both traveling at high speeds. This alone presents a level of difficulty that would surpass the coordination skills of many individuals. To augment this difficulty, in recent years the average Major League Baseball (MLB) four-seam fastball velocity has hovered around 93 miles per hour, according to Tom Verducci from *Sports Illustrated* (Verducci, 2018). This pitch speed allows the batter a response time of approximately 440 milliseconds with the current dimensions of a baseball field, which is reduced as the pitcher's release point and the batter's contact point with the ball shortens the distance of 60.5 feet between the front of the pitching rubber and rear of home plate. Hitting a baseball consists of sensorimotor coordination in a full-body movement that requires temporal and spatial accuracy with minimal latency.

Hitting a baseball can be simulated in the simplest training form as a closed motor skill by using a batting tee. However, in reality, it is an open motor skill that requires a sensorimotor response. In a simple response task scenario, the sensorimotor response process only requires a stimulus detection and motor execution stages. A simple response batting task can be simulated with the use of a pitching machine as the trajectory and speed of the baseball are controlled. However, hitting a baseball in a game scenario is not this simple, and the trajectories will not likely be the same. Therefore, a batter must also determine the location of the pitch which dictates whether or not a swing should a occur similar to a go/no go discrimination task that incorporates an extra stage of stimulus discrimination in the response process. If a pitch crosses the plate outside of the strike zone a swing should be avoided, and the pitch should be taken.

Variation in the pitch location amplifies the difficulty associated with a simple response task and results in an increased in required response time for success. With regard to different pitch types, both the speed and trajectory of a pitch can be altered which upgrades the task further to a choice response task, adding an additional stage of response selection in the process and further increasing the required reaction time for success (Miller & Low, 2001). Inter-trial variability is increased with pitch type and location which increases the complexity of the task.

Considering that in the most favorable conditions it is possible for an individual to produce the simplest voluntary response to a visual stimulus in 150 milliseconds and that in reality this response time is around 250 milliseconds, there is little time for a batter to visually track a pitch and then produce the swing to create contact with the ball, especially in a realistic scenario of choice sensorimotor response which has shown to increase reaction time (Miller & Low, 2001; Donders, 1969; Henry & Rogers, 1960). With a fastball permitting less than 440 milliseconds to respond and response processing demands requiring at least 250 milliseconds, although this reaction time requirement is likely longer, there is less than 200 milliseconds allotted for the production of the correct response movement. Additionally, the movement time associated with pressing button from which this response time data is derived is less than that of a baseball swing due to movement complexity of a coordinated, full body motion; movement time is dependent on response complexity (Anson, 1982). However, it is important to note that the movement time of the response remains consistent with the progression from a simple to a choice response task (Henry & Rogers, 1960; Gavkare, Nanware, & Surdi, 2013). Research indicates that these movement times can be improved through practice and training (Fischman & Lim, 1991). Athletes have displayed faster response times compared to nonathletes in both visual and whole-body response tasks (Mowbray & Rhoades, 1959; Gavkare et al., 2013; Akarsu, Caliskan, & Dane, 2009). Traditional baseball batting training strategies emphasize the mechanics of the swing through repetitional practice, permitting a batter limited success with an improbable task.

Significance of the Problem

As a result of the temporal constraints associated with the task of hitting a baseball, the advantage is given to the pitcher in terms of success; the closed motor skill of pitching is less complex than the open motor skill of batting (Gentile, 1987). In recent years, the pendulum has swung further in favor of the pitcher in terms of performance. It is commonly believed that higher pitch velocities has resulted in this trend, but statistics show that the average pitch velocity in the MLB has not changed in recent years. Different pitch types seem to be providing the edge to pitching as a result of this choice sensorimotor task phenomenon that is limiting success. As previously stated, altering the pitch type causes variance in the flight path and time, making the task of hitting a baseball more difficult. It has been established that as the number of possible choices associated with a movement increases, the decision time of that movement also increases (Hick, 1952; Hyman, 1953). The more possible pitch types a batter can potentially see from a particular pitcher during an at-bat increases the difficulty of hitting the baseball and limits success. Combining the variation of pitch types with the contemporary strategy of batters to hit for power over contact and strive for home runs has resulted in diminished league-wide batting statistics.

With the exhaustive MLB sabermetrics that characterize the game of baseball, it can be seen that over the past decade fastball velocities have relatively remained the same, but the percentage of breaking balls thrown has increased while fastball usage has decreased. Furthermore, the batting average against breaking balls is about 50 points less than a fastball

(Verducci, 2018). Pitchers are taking full advantage of this phenomenon as the 2018 MLB batting average is the lowest it has been since 1972 and the strikeout rate has consistently increased to an all-time high of 8.81 strikeouts this past season; almost one of every three outs recorded results from a batter not being able to hit the ball (Baseball-Reference). Other approaches to the game have also aided in the reduction of batting performance, such as the defensive strategies in the form of the shift for certain batters which has helped limit batting average. Therefore, as opposed to traditional training methods that emphasize reducing the movement time of the response process proving to be insufficient in increasing performance, training should also incorporate methods to increase the reaction time of the response process to produce a more effective response permitting increased success.

The task of hitting a baseball permits success rates of only 30% in the most elite batters; these rates seem to be dropping as pitching continues to dominate the game. Although the hitting performance of MLB players is deteriorating, the average salary of these players continues to increase and has almost doubled from $2.37 million in 2003 to $4.52 million this season (Statista). According to Forbes, the value of the MLB is just under $50 billion (Forbes). In an occupation where salary is dictated by performance, and a slight statistical increase in hitting performance corresponds with millions of dollars, there is an existing pressure to gain a competitive edge by players. This is not always accomplished by legal or ethical means; performance enhancement drugs have traditionally plagued the game of baseball and its elite hitters as contemporary training strategies are inadequate. Considering the amount of money invested into this game and its players, for example this year’s record breaking $430 million deal for Mike Trout, it is essential to level the playing field between the open motor skill of hitting and the closed motor skill of pitching where the latter has the clear competitive edge; the need for developing effective hitting training strategies to improve performance is apparent.

Previous Research

Given the value of quality batting there are several approaches to training to improve success. The most effective training methods can be developed by identifying variables that are relevant to performance and correlate with skill level. The traditional training method widely utilized by coaches, encompassing the motor aspect of the baseball swing, focuses on strength training to decrease the movement time of the sensorimotor response by reducing the rotational swing motion duration through the production of a faster swing; this generates enhanced kinematics to produce better contact. Batting performance has displayed a correlation with the strength of the forearm, wrists, and the rotational strength of the torso and pelvis (Szymanski & DeRenne, 2010; Szymanski et al., 2007; Szymanski et al., 2006). The alternative and more recent training modality, encompassing the sensory aspect of the baseball swing, focuses on vision training to decrease the required reaction time of the sensorimotor response by increasing the tracking duration through improved pitch tracking.

Vision training has shown to decrease the required reaction time for success, as well as correlates to increased hitting performance (Maman, Gaurang, & Sandhu, 2001; Kohmura & Yoshigi, 2004; Clark, Ellis, Bench, Khoury, & Graman, 2012). However, as vision training is contemporary, its relationship to sports performance is still controversial (Khanal, 2015; Knudson & Kluka, 1997; Wood & Abernethy, 1997). In order to further develop more effective training strategies, sensorimotor variables related to skilled batting in baseball need to be identified.

Research dedicated to identifying relevant variables to hitting a baseball has, similarly, been based on either sensory or motor aspects of the baseball swing independently. Studies emphasizing vision comprise the majority of the sensory aspect of batting and analyze how a batter tracks a pitch. There are four types of eye movements; these are smooth pursuit, saccadic, vergence, and vestibulo-ocular movements. Vergence movements refer to the simultaneous rotations of the eyes in opposite directions to focus on an object at different distances, while vestibulo-ocular movements accommodate for head movements to maintain focus. Saccadic eye movements are rapid movements between focal points. Conversely, the slower movements used to track an object as it moves are smooth pursuit eye movements (Pruves, 2001). The most prominent type of eye movements utilized while tracking a baseball are smooth pursuit movements, which are essential for pitch tracking early in the pitch flight, and saccadic eye movements (Bahill & McDonald, 1983; DeLucia & Cochran, 1985; Croft, Button, & Dicks, 2010; Schalen, 1980).

Regarding eye movements, there is variance in the tracking strategies used by players. Skilled hitters have pitch tracking strategies associated with a greater reliance on smooth pursuit eye movements and less saccades allowing for more accuracy between ball trajectories and gaze vectors (DeLucia & Cochran, 1985; Takhashi, Uemura, Fujishiro, 1983). These batters have also displayed an enhanced head and eye rotational coordination to produce a greater gaze velocity that is indicative of skill and allows for an increased tracking duration where gaze would typically fall behind and rely on saccades, also resulting is less gaze error. Batters do not use vergence eye movements and vestibulo-ocular suppression has been observed, supporting the idea of improved head coordination and the importance of smooth pursuit tracking. (Bayhill & LaRitz, 1984; Hubbard & Seng, 1954; Uchida, Kudoh, Higuchi, & Kanosue, 2013; Uchida

Kudoh, Murakami, Honda, & Kitazawa, 2012; Fogt & Perrson, 2017; Fogt & Zimmerman, 2014; Takahashi et al., 1983; Mann, Heaton, Kryskow, Maule, & Ghaiar, 2013). Additionally, it has been observed that eye movement latency from the pitch release is reduced in skilled hitters (Uchida et al., 2013; Uchida et al., 2012; Land & McLeod, 2000). The ideology behind the relationship of the sensory component of the baseball swing and performance is increasing the decision time and decreasing the reaction time by tracking the ball earlier through shorter eye latencies, and also by tracking the ball longer through greater gaze velocities.

While visual studies encompass the sensory aspect, biomechanical studies comprise the motor aspect of batting and analyze how a batter produces a swing. The swing is generated from the utilization of a kinetic chain originating from ground reaction forces and terminating in the ball, with the goal of maximizing its exit velocity, as energy is transferred from the lower extremities to the upper extremities to produce the movement of the bat (Welch, Banks, Cook, & Draovitch, 1995; Fortenbaugh, Fleisig, Onar-Thomas, & Asfour, 2011). Due to the nature of the task, temporal analysis of this baseball swing kinetic chain is common. With regards to timing, a swing is often broken into different phases for temporal analysis (Nakata, Miura, Yoshie, Kanosue, & Kudo, 2013; Fleisig, Hsu, Fortenbaugh, Cordover, & Press, 2013; Shaffer, Jobe, Pink, & Perry, 1993). The specific phases can differ however a simple disintegration of the swing includes a loading, landing, and launching phase. The loading phase consists of a motion in the direction opposite the ball and ends when peak displacement in that direction occurs; the batter's front foot typically raises off the ground. The landing phase consists of a motion towards the ball and ends when the front foot reestablishes contact with the ground. The launching phase consists of the rotational motion that produces the swing and ends when bat-ball contact occurs. With regard to these phases, the loading and landing phases occur regardless of if a batter decides to take a pitch or produce a swing. If the decision to swing is made, the launching phase will be executed. Therefore, pitch tracking to visually analyze the trajectory and decide whether to swing occurs during the loading and landing phases.

It is commonly believed that the trunk, more specifically the pelvis, play a crucial role in a batter's hitting performance and generating power throughout the phases of the swing (Williams & Underwood, 1986). Greater pelvis displacement, as well as a pelvis rotational velocity, has been observed to correlate with skill (Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014; Inkster, Murphy, Bower, & Watsford, 2011). These advanced pelvis kinematics allow for an increased bat end velocity to produce greater batted ball exit velocities. Therefore, bat end velocity has also been identified to be indicative of skill level (Szymanski, DeRenne, Spaniol, 2009; Szymanski et al., 2010; Welch et al., 1995; Tabuchi, Matsuo, & Hashizume, 2007). The ideology behind the relationship of the motor component of the baseball swing and performance is decreasing the movement time by decreasing the launch phase duration through greater pelvis displacement and velocity resulting in greater bat end velocities.

Previous baseball research has also examined the effects of manipulating the response process, through different pitch conditions, on swing kinematics. However, the results have been inconclusive as one study observed reduced kinematics from an inhibited response due to higher pitch speeds while the other observed enhanced timing due to the known pitch condition (Miaynishi & Endo, 2016; Takuo, Norihisa, Sekiya, & Mitsura, 2008). Neither study examined pitch tracking or swing kinematics as a result of the whether the pitch is known. Also, neither study incorporated skill level of the batters as a factor. Furthermore, previous research fails to examine the effects of sensory kinematics exhibited through pitch tracking on the motor kinematics produced through the swing, presenting an additional void in the literature.

Scope of the study

Hitting a baseball is an interceptive sensorimotor task that consists of coordination in a full body movement, requiring temporal and spatial accuracy. Previous research has led to the identification of both sensory and motor variables that are determinant of skill and generates the idea that the batter utilizes visual kinematics to increase the pitch tracking duration and motor kinematics to decrease the swing movement duration, which is the emphasis of training strategies. It is essential to examine the phenomenon of alterations in the response process, dictated by changes in the sensorimotor task, and how swing kinematics are affected. As hitting a baseball requires sufficient sensorimotor coordination, it is important to fully comprehend how the movements of the response, in terms of the swing mechanics, are dependent on the reaction to the stimulus, in terms of pitch tracking. The ideology of this relationship is that greater visual kinematics, in regard to rotational displacement and velocity, to enhance the detection of sensory information of a pitch will permit a batter more temporal and spatial accuracy allowing for enhanced motor execution through greater swing kinematics. Through a thorough understanding of this sensorimotor coordination, additional training modalities can be discovered to increase batting performance. Analyzing the kinematic alterations that occur from different sensorimotor conditions, along with relationship between the sensory and motor aspects of hitting a baseball as they relate to performance, can potentially turn the tide in favor of the batter in a game currently dominated by pitching.

Hypothesis and purpose

The purpose of this study was to perform kinematic analysis and measure the sensorimotor factors indicative of skill, along with the durations of the swing phases, in different pitch conditions to understand the changes that occur as a result of whether the pitch type is known, with elite and sub-elite batters. A second purpose of this study was to analyze the sensorimotor relationship between the visual and biomechanical kinematics associated with hitting a baseball that influence performance. All kinematic data was analyzed for pitch type and skill level. It was hypothesized that increased rotational displacements and velocities are associated with the known condition and elite group. Another hypothesis is that the known condition and elite group will produce longer loading and landing phases with shorter launching phases. It was also hypothesized that visual kinematics positively correlates with swing kinematics.

Chapter II: Review of Literature

Response time in sensorimotor tasks

Sensorimotor skills are a significant component of performance in sports. Baseball batting requires adequate sensorimotor skills with precise timing while rapidly responding to a pitch. Simplistically, these skills refer to an individual's efficiency in a task that involves a response to a stimulus. However, this response is more complex and involves the stages of sensation perception, response selection, and response execution according to the model provided by Wickens (Wickens, 1980). This complexity leads to questions about how quickly an individual can produce a response, which is the basis of Donders' contributions. He conducted a fundamental research study that was the first to measure response times of different tasks through various forms of stimuli such as somatosensory, auditory, and visual stimuli. The results of the experiment showed differences between the times associated with the type of stimulus, as well as the task. The five subjects showed that in a simple task the average response time to a light visual stimulus was 154 milliseconds. This time increased with the task complexity (Donders, 1969).

Baseball batting, however, is not a simple response task. A batter must decide whether the pitch is going to be a inside the strike zone, dictating whether or not a swing should occur. This situation represents a discriminate task more commonly referred to as a go/no go task. Building off of Donders' findings, a similar study was conducted to analyze the differences in response times between a simple, go/no go, and choice response tasks using a computer screen and appearing letters that corresponded with a key to press. The results showed an increase in the response times from simple tasks to choice response tasks. The average response times were 347, 395, and 441 milliseconds for the simple, go/no go, and choice conditions respectively, supporting the findings of Donders (Miller & Low, 2001).

The previously described go/no go task of baseball batting becomes further complex with the inclusion of pitch type. As different pitches vary in velocity and trajectory, altering the type of pitch will upgrade this scenario to a choice response task as the batter must elicit the correct response based on the pitch type, thus increasing the response time and decreasing the success of the batter. Hick's Law further describes this phenomenon and was established through a study that analyzed response times with different choice reaction tasks by altering the number of potential choices. This was completed using a display screen and a different key for each finger that corresponded with a specific stimulus; each key represented the number of possible choices. Response times were measured at all levels from one choice to 10 choices. The results showed a logarithmic relationship describing the increasing amount of time it takes to respond to a stimulus as the number of choices (Hick, 1952). Similarly, using visual display with lights for the stimuli and altering the number of potential choices, as well as the probability of those choices occurring, a similar relationship was determined. It was concluded that the response time was impacted by the number of choices possible and the probability of those choices occurring (Hyman, 1953).

As hitting a baseball is a full body movement, compared to the methods used in the studies that derived this response time data of a finger pressing a button, movement complexity is a factor in the response time. A study used a simple task requiring a finger movement response and compared the duration to that of an arm movement response to examine the effects of movement complexity. A button was used for the finger movement while a tennis ball hung by a string that was attached to the button was used for the arm movement. The results showed an increase in the response time associated with the complexity of the movement. A 20% increase in response times were observed between finger and arms movements, as well as an addition 7% increase for more complex arm movements. The results also showed that the type of movement utilized impacted response times more so than the speed of the movement (Henry & Rogers, 1960).

As the task of swinging a baseball bat requires full body movement and coordination, it can be described as a complex task and would therefore require greater response times in comparison to a simple finger movement. As hitting a baseball is dependent on precise timing and a quick response, the question emerges of whether or not these response times can be improved or if individuals have an innate ability that makes them more inclined to be successful at hitting a baseball. While some would argue that individuals are predisposed, research suggests that response times can be decreased. With the inclusion practice over time and a similar setup as Hick used in his choice response task experiment, a study was able to show a reduction in the response time of the same task with practice. Additionally, it was noted that the increase in response time with the number of potential choices described by Hick and Hyman did not occur with significant practice when there were between two and four possible choices (Mowbray & Rhoades, 1959). A number of research studies have identified sensorimotor differences between athletes and nonathletes as a result of extensive practice. Response times were measured at 318.1 and 369.4 milliseconds for athletes and nonathletes respectively using a computer screen to display the stimuli and a button for the response (Akarsu, Caliskan, & Dane, 2009). Similarly, using a red and green light for buttons corresponding to each hand, athletes responded quicker than nonathletes in all conditions (Gavkare, Nanaware, & Surdi, 2013).

As the sensorimotor skills required for quality performance vary depending on the specific sport, it is important to analyze the response times of individuals from different sports domains. Generally, sport specific tasks can be broken into two distinct categories, open and close motor skills; hitting a baseball represents an open motor skill as the task is initiated by the pitcher. A study looking at volleyball players and sprinters, representing the closed and open skill-dominated sports respectively, used a speed, anticipation, and reaction time test to measure six sensorimotor tasks. The results showed that sprinters had decreased auditory response times than volleyball players, but no differences in visual response times were observed. Additionally, the anticipatory skills displayed by volleyball players were superior to those of sprinters. These support the ideology that sensorimotor skills are trainable and can be improved with effective practice (Nuri, Shamehr, Ghotbi, & Moghadam, 2013).

The question remains as to how these sensorimotor enhancements translate to the performance in an athletic setting. A study dedicated to investigating this conducted visual examinations, as well as physical examinations for movement timing, on college, high school, and rejected baseball players and compared these results to the statistics of batting average, slugging percentage, and runs batted in. However, no correlation between the batting performance statistics and the results of the vision and timing tests although differences in the vision and timing between groups were observed was found (Winograd, 1942). Conversely, similar research used the Nike Sensory Station, which measures nine sensorimotor tasks, and compared these results to various baseball statistics. Correlations exist between various sensorimotor skill and batting performance values of on-base percentage, walk rate, and strikeout rate; the majority of the relationships were observed with strikeout rates while response time correlated with walk rate statistics were observed (Burris et al., 2018). Similarly, the same sensorimotor assessment was used to distinguish characteristics between pitchers and hitters at the high school, collegiate, and professional levels. However, the only relationships observed that distinguished pitchers from hitters occurred at the professional level with visual clarity and depth perception; no relationship was observed with response time at any level (Klemish et al., 2018). Additionally, the relationship between various batting statistics and visual skills using Vizual Edge software was examined in 2014. The vision scores determined by the computer program found correlations with batting average, strike out rate, on-base percentage, and on-base plus slugging percentage; batting average was shown to correlate with response time (Spaniol et al., 2014).

Sensory aspect of skilled batting

The question of what visual characteristic are exhibited by skilled batters is age-old as baseball research is not new to the scientific community. In 1925, a preliminary study at Columbia University analyzed Babe Ruth through eye tests and determined that his eyes were 12% faster and 90% more efficient than average humans, resulting in an enhanced pitch tracking ability allowing for greater performance. This data was determined by measuring response time to a light stimulus by pressing a button. Additionally, eight letters would be displayed on a screen for 50 milliseconds. Ruth was able to read six as compared to the average of four and a half letters (Johanson & Holmes, 1925).

As hitting a baseball requires the capability of visually tracking a pitch, understanding the eye movements that while batting is important to identify factors relating to skill. There are four possible types of eye movements; these are smooth pursuit, saccadic, vergence, and vestibulo-ocular movements. Vergence movements refer to the rotations of the eyes to focus on an object at different distances, while vestibulo-ocular movements accommodate for head movements to maintain focus. Saccadic eye movements are rapid movements between focal points. Conversely, the slower movements used to track an object as it moves are smooth pursuit eye movements; the latter two movements allow a batter to track a baseball as it is pitched (Pruves, 2001). A greater reliance on either saccadic or smooth pursuit eye movement is influenced by the target velocity of the object being tracked (Takahashi, Uemura, & Fujishiro, 1983). A study attempted to determine whether it was necessary to track the entirety of a pitch for success by using a screen to obstruct the view of the ball during different sections of the pitch. It was observed that batters can use information obtained from tracking a portion of the pitch trajectory to determine the point of contact (DeLucia & Cochran, 1985). Because of this, there is variance in the tracking strategies used by players (DeLucia & Cochran, 1985; Croft, Button, & Dicks, 2010).

Vision has been frequently studied to identify factors relevant to batting performance. In 1954, Hubbard and Seng analyzed professional and collegiate baseball players through video observation during batting practice in a preliminary study. They concluded that due to the high angular velocities of the ball relative to the batter, the inability to track occurred between 8 and 15 feet from home plate (Hubbard & Seng, 1954). As players are not able to track the ball throughout the pitch, some batters will have a greater reliance on saccadic movements to predict the location. A study incorporating a photoelectric system was used to measure eye movements as they tracked a red laser on a screen as it moved. Eye tracking that consists of more saccadic movements is associated with higher error in gaze position and timing than eye tracking with players who can produce smooth pursuit eye movements for longer durations at higher velocities (Bayhill & McDonald, 1983, Croft, Button, & Dicks, 2010; Takahashi, Uemura, & Fujishiro, 1983).

Although the ability to smooth pursuit track at high velocities is critical to batting performance, by moving a dot across a screen at different target speeds it was identified that humans are not able to accurately, at a 90% gain of the target velocity, track an object moving greater than 50 degrees per second (Schalen, 1980). However, this also shown to occur at 100 degrees per second in another study (Meyer, Lasker, & Robinson, 1985). Saccadic eye movements were primarily used at higher velocities (Schalen, 1980; Meyer, Lasker, & Robinson, 1985; Fogt & Persson, 2017; Fogt & Zimmerman, 2014; Maruta, Heaton, Kryskow, Maule, Ghajar., 2013).

Building on his previous research, Bahill wanted to further study eye movements, as well as include head rotations, as a batter tracked a baseball. Using graduate students, collegiate baseball players, and a professional baseball player, they simulated a fastball and analyzed pitch tracking. The fastball was simulated using a pulley system connected to a monitor. Eye movements were monitored through infrared emitters and photodetectors while the head movements, using light-emitting diodes, were captured by a camera mounted on the ceiling. This experiment did not accurately mimic a batting scenario as it was indoor, no swing occurred, and the ball was attached to a horizontal pulley system neglecting gravitational effects; there was no vertical displacement of the ball and only horizontal movements were analyzed. The pitch was also set to a point high and outside with no variance to better observe the head rotations and eye movements. It was concluded that batters use both their head and eyes to track a pitch. On average, students tracked the ball to a point 9 feet in front of the plate before their gaze fell behind; their maximum velocities were 70 degrees per second as their eyes traveled at 50 degrees per second while the head moved at 20 degrees per second. The professional player showed superior tracking skill in that he could track the ball longer, to a position 5.5 feet from home plate, with quicker smooth pursuit movements, having maximum gaze velocity of 150 degrees per second from eye and head rotations of 120 degrees per second and 30 degrees per second respectively. It is important to note that this was quicker than any previous recorded eye movements in humans (Bahill & LaRitz, 1984).

Supplementing the gaze velocity research in baseball players, two studies were conducted to compare the gaze velocities of athletes and nonathletes by projecting Landolt C rings, a shape closed on three sides with an opening on the fourth similar to the letter ‘C,’ across a screen. The participants were instructed to determine the orientation of the C ring, it terms of the direction the opening of the ring, as it cross the visual field at different from 100 to 900 degrees per second; a correct response threshold was set at 75% at any given velocity. Baseball players were able to determine the correct orientation on average at 520 and 413 degrees per second as compared to the 486 and 393 degrees per second in nonathletes for the experiments conducted in 2012 and 2013 respectively (Uchida, Kudoh, Higuchi, & Kanosue, 2013; Uchida Kudoh, Murakami, Honda, & Kitazawa, 2012). It is important to note that correct response rates at 700 degrees per second fell below chance level for nonathletes only and neither group had achieved above chance level at 800 degrees per second or greater; this infers that baseball players were able to view objects at a greater velocity.

An additional finding in the Bahill and LaRitz study was that the professional player better replicated his movements with more consistency between each of his trials, inferring a developed coordination of enhanced movements in expert baseball players. Batters did not use vergence eye movements and vestibulo-ocular suppression was observed, supporting the idea of improved head coordination and the importance of smooth pursuit tracking (Bahill & LaRitz, 1984). Therefore, eye and head movement coupling has been a topic of research with hitting a baseball.

This vestibulo-ocular suppression was also observed in a study that observed head and eye movements in college baseball players at 50 millisecond intervals. The study used a pitching machine to project tennis balls, eye tracking glasses for eye movements, and inertial sensors for head rotations. The tennis balls had either red or black numbers and they players were instructed to view the ball, not swing, and name the color and number; the players were not able to state the color and number accurately in the study. It was observed that players primarily track the ball with larger head movements while eye movements facilitate tracking later in the pitch trajectory (Fogt & Zimmerman, 2014).

These results were seen in a similar study that also included a swing condition. While tracking without a swing batters used their heads primarily while the larger eye movements did not occur until later in the pitch. However, the swing trials showed that head movements were larger than those of the eyes throughout the entirety of the pitch. The study also found that gaze was directed near the ball in the take trials until approximately 150 milliseconds prior to the ball crossing the plate when saccade established gaze ahead of the ball, whereas gaze near the ball was maintained longer to approximated 50 to 60 milliseconds prior in the swing trials (Fogt & Persson, 2017).

Head and eye rotations were also analyzed to explain the coordination possessed by expert batsmen in a 2013 Cricket study. Using a bowling machine for consistency, the study analyzed the eye and head rotations of elite and recreational batsmen using the Mobile Eye tracking system. The elite batsmen displayed the ability to couple the movement of the head rotation to the position of the ball more precisely (Mann, Spratford, & Abernethy, 2013). This literature also supports the idea of coordinated movements of both the head and eyes to produce higher gaze velocities to track a pitch (Bahill & LaRitz, 1984). Therefore, research has observed a relationship between batting performance and gaze velocity.

Temporal aspect of skilled batting

As gaze velocity limits tracking towards the end of a pitch's trajectory, eye movement latency places limitations at the beginning. Due to the nature of the task, timing is an essential determinant of batting success rates and indicative of sensorimotor coordination. Baseball literature consists of various studies that analyze coordination through both sensory and motor aspects of batting in relation to time. It is commonly thought that baseball player have improved reaction times represented by eye movements occurring earlier in relation to the pitch flight. However, a study in 1987 looked at eye latencies between expert and novice batters and found no difference between the reaction times of the two groups; novices and experts had an average of 152.46 and 151.47 respectively (Shank & Haywood, 1987). Similar results of a 150-millisecond average latency were observed in baseball players during the study conducted by Bahill and McDonald, which also concluded that this latency can be reduced with practice (Bahill & McDonald, 1983).

More recently, timing had been researched in both a baseball and cricket experiment. The cricket study used a bowling machine and eye tracking glasses in a batting cage while the baseball study used a projection screen to move Landolt C rings across it at different orientations and target speeds to analyze eye movements. Eye latency was measured at target speeds from 200 to 900 degrees per second between athletes and nonathletes. The baseball players had reduced latencies for target speeds of 200 to 600 degrees per second and were the only group to produce eye movements at the 700 degrees per second velocity; at 700 degrees per second the rings were projected too quickly for a nonathlete to produce and eye movement before it crossed the screen. Neither group were able to view objects moving at 800 degrees per second or greater (Uchida, Kudoh, Higuchi, & Kanosue, 2013). Contradicting the previous latency research in 1987, each of these studies concluded that skill level was associated with eye movements occurring at shorter latencies (Land & McLeod, 2000; Uchida, Kudoh, Higuchi, & Kanosue, 2013). Therefore, a relationship between enhanced batting performance and earlier eye movements has been observed.

Biomechanical elements of a baseball swing have also been analyzed in relation to time. Batting coordination through head position has been studied as it relates to skill level. Head position is separate from head movements. The head moves rotationally to track a ball while the head position changes as a result of the weight shifting in a translational manner during swing biomechanics. The head position of skilled and novice batsmen was investigated using high speed cameras. Head position was mapped in both horizontal and vertical directions. The peak value horizontally was measured as the head position furthest from the pitcher, while the head position closest to the ground represented the peak position vertically.

The latencies at which these values occurred, as well as the difference between the horizontal peak position and position at impact, were calculated. The variability of these values from each pitch was recorded. Differences were found between the skilled and novice groups in horizontal peak latency, difference between peak and impact positions, and variability in both directions. The skilled batters had a horizontal peak value occurring on average at 662 milliseconds before impact and moved their heads 12.5 centimeters towards the pitcher, while the novice group had a peak latency average of 408 milliseconds and moved their heads 6.0 centimeters. The horizontal peak value represents the shifting of the weight to the back foot in the loading phase at the start of a swing. This occurred earlier in skilled players indicating they started their swings sooner because of enhanced timing. The difference between the peak value and impact position represents the weight shifting forward during the launching phase of a swing. The skilled players had greater forward displacement before impact. The variability of horizontal peak latency was 72 and 157 milliseconds and the variability of the vertical peak values was 1.3 and 2.1 centimeters for the skilled and novice groups respectively. This indicates that skilled players are much more consistent with their swing motion and timing, exhibiting enhanced coordination (Nakata, Miura, Yoshie, & Kudo, 2012). It is unknown whether this is due to improved sensory or motor skills.

A full body electromyographical study was designed to analyze the coordinated sequence of muscular activity during a swing. A sequence of activity beginning in the pelvis, migrating then to the trunk, and finishing with arm activation was observed (Shaffer, Jobe, Pink, & Perry, 1993). Due to the implicit full body coordinated movement characteristic of a baseball swing, Nakata was also involved in a study that analyzed the muscle activity of 8 lower limb muscles through electromyography. The muscle activity of skilled batsmen was compared to that of unskilled batsmen at four different phases during the swing. Like his head position study, the onset of muscle activity showed that the swing timing occurred earlier in the skilled group at each phase (Nakata, Miura, Yoshie, Kanosue, & Kudo, 2013).

Ground reaction forces have also been measured in baseball research to analyze swing timing. Batters utilize the ground reaction forces to generate power which is eventually transferring to the arms to product a swing. As the ground reactions forces initiate the swing, analyzing the time these occur relative to the pitch is important. To examine this in collegiate baseball players, force plates, a pitching machine, and a high-speed camera were used to demonstrate the relationship between swing timing and pitch speed through ground reaction forces at different phases of the swing. The step that initiates the swing to shift the weight forward was dependent on the speed of the pitch. As the temporal variability at the beginning phase of the swing existed between trials, there was a reduction in this variability as the swing progressed through the later phases until contact. It was concluded that a compensatory mechanism is exhibited by skilled batters with regards to timing the swing to create contact regardless of pitch speed (Katsumata, 2007). This supports the idea of enhanced sensorimotor coordination essential to timing among skilled batters.

Incorporating pitch types that alter the speed and trajectory of a pitch causes the task the timing of the swing to produce contact much more difficult. To demonstrate this, similar research was conducted to analyze the timing differences of the swing, measured through ground reaction forces, as a batter faced fastballs and changeups. The study used live pitching in an indoor setting with force plates. Supporting the previous findings, batters shifted their weight backwards to initiate their swing at the same time, however the forward step occurred at different times based on the pitch speed. This occurred earlier in the changeup trials as compared to the fastball trials relative to contact (Fortenbaugh, Fleisig, Onar-Thomas, & Asfour, 2011).

This phenomenon can be attributed to difficulty visually distinguishing pitch type resulting in spatial and temporal errors that limit success. A baseball batting simulation was utilized to examine this further. Using collegiate baseball players, variance in the pitch speed resulted spatial errors that were greater than temporal errors. This infers that the pitch trajectory of altering pitch types has a greater influence on performance than does speed. The findings included that accuracy was improved when additional information about the pitch type was provided; it can be derived that enhanced pitch tracking will increase this accuracy, and therefore performance (Gray, 2002).

Complementarily, research has investigated temporal differences in relation to velocities of the trunk and bat during a known and unknown pitch type; swing phases were also analyzed. Greater variance in phase durations were observed with the unknown pitch type. However, while consistencies were observed when the pitch was known, the average velocity of the pelvis and the maximum velocity of the bat were greater in the unknown condition; the study attributed this to more time being dedicated to the sensory aspect of the task permitting less time for the motor component (Miaynishi & Endo, 2016). Controversially, a relationship has also been documented between swing kinematics and the pitch speed in a study via motion capture and a pitching machine set to one of two speeds. The greater pitch speed, which also permits a shorter movement time for success, was associated with reduced pelvis and bat kinematics to maximize accuracy that is limited by time, even with the trajectory known (Takuo, Norihisa, Sekiya, & Mitsura, 2008). Therefore, as one study observed increased kinematics as a compensatory response and the other observed decreased kinematics as an inhibited response, research has been controversial on the effects of the response process on swing kinematics.

The specific swing phases determined are subjective to the researcher and differences do exist between research studies. However, a combining the phases that are consistent across all baseball batting phase methodologies, a simple disintegration of the swing results in three phases; these are the loading, landing, and launching phases. The loading phase of the swing is initiated as the batter's weight shifts in the direction opposite the pitcher and terminates when peak displacement in that direction occurs; the front foot will often lift off the ground during this phase. The landing phase initiates when the batter's weight is shifted back towards the pitcher and terminates when the front foot re-establishes contact with the ground. The launching phase is initiated as the batter's pelvis begin the rotational motion of the body and terminates at the point of contact between the bat and the ball (Miyanishi & Endo, 2016; Shaffer, Jobe, Pink, & Perry, 1993; Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014; Messier & Owen, 1985; Fleisig, Hsu, Fortenbaugh, Cordover, & Press, 2013). This simple swing disintegration allows for the temporal analysis of specific swing events and characteristics.

Motor aspect of skilled batting

Identifying which kinematic values of the swing impact performance it is essential to understand the well-established kinetic chain that transfers energy throughout the body to create a powerful swing. Lower limb electromyography and ground reaction forces are often analyzed in baseball research from a power generation perspective; however, the baseball swing is a coordinated whole-body motion where energy is transferred from the lower limbs to the upper limbs. This literature also supports the idea of power being generated by the pelvis (Williams & Underwood, 1986). Through motion capture and electromyography, it has been determined that the batter's weight shifts backward and forward through the swing, the pelvis and trunk rotate to produce the swinging motion of the upper body and bat; energy transfers from the ground reaction forces to the lower extremities, which is transferred to the trunk and terminates in the arms (Messier & Owen, 1985; Shaffer, Jobe, Pink, & Perry, 1993; Welch, Banks, Cook, & Draovitch, 1995; Reyes, Dickin, Crusat, & Dolny, 2011). Therefore, pelvis and trunk biomechanics are often analyzed during a baseball swing.

Differences in trunk kinematics have been observed in relation to batting skill. A research study measured the differences in trunk rotation between skilled and unskilled batsmen using high-speed cameras and body markers. The difference between the angular displacements in the upper torso and pelvis were larger in the skilled group at 126.1 degrees and 99.6 degrees respectfully. These values are compared to the upper torso 79.5 degrees and pelvis 61.0 degrees of angular displacement. While the displacement was greater, the timing of the maximum pelvis angle during loading was occurred later at 392 milliseconds before impact in the skilled group. The maximum angle in the unskilled group occurred earlier at 518 milliseconds before impact. The great displacement is shorter time resulted in differences of the peak angular velocities of 984 degrees per second in the skilled group compared to 587 degrees per second in the unskilled group. It is important to note that skilled players displayed more consistent timing of peak angular velocity of within 7 milliseconds compared to variability of 62 milliseconds in the unskilled group. This further supports the improved sensorimotor coordination relationship with performance (Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014).

Expanding on this, another study incorporated bat velocity into a similar study where knee, pelvis, and elbow kinematics were calculated using infrared cameras and body markers. The purpose of the study was to identify kinematic differences with skill level. There were differences in bat velocity. Skilled players produced greater bat velocities at 36.8 meters per second compared to 33.8 meters per second. The maximum angular velocity of the pelvis approached significance at 897.2 degrees per second and 836.2 degrees per second in the skilled and unskilled groups respectively (Inkster, Murphy, Bower, & Watsford, 2011).

A comparison between adult and youth hitters identified kinematic differences with the pelvis and bat. Adults produced an average peak pelvis velocity of 857 degrees per second, whereas the youth group produced 717 degrees per second. The bat velocity at the point of contact was 30 and 25 meters per second on average for the adult and youth groups respectively (Escamilla et al., 2009). It is a common ideology that bat velocity is indicative of batting performance. An increased bat velocity correlates with an increased decision time, decreased swing time, and increased batted-ball velocity; as the objective is to produce quality contact with the ball, there is a relationship between batted-ball velocity and skill level of batters (Szymanski, DeRenne, Spaniol, 2009).

Effective strategies for baseball swing training

Various strength training techniques attempt to improve the motor aspects of baseball batting linked to performance. Upper body strength has been identified as a factor of bat velocity. Wrist and forearm strength was measured and compared to bat velocity over a 12-week resistance training period. All groups displayed increases in bat velocity, as well as increased wrist and forearm strength, over the training period; however, the group that received additional resistance training, specifically for the wrist and forearm, did not show further increases in bat velocity (Szymanski et al., 2006). It is inconclusive as to whether additional wrist and forearm training is beneficial to batting performance (Szymanski & DeRenne, 2010). Chest strength was also analyzed and compared to bat velocity. However, while the results of one group showed a relationship between chest strength and bat velocity via a one repetition maximum bench press, the second group did not (Miyaguchi & Demura, 2012).

As pelvis kinematics are indictive of batting performance, trunk strength training programs have also been examined and compared to bat and pelvis velocity. After a 12-week resistance training period, both groups showed increased in pelvis velocity and bat velocity, while the group receiving additional rotational medicine ball exercises displayed greater improvements (Szymanski et al., 2007). Similarly, a 12-week resistance training study identified that full-body resistance training with emphasis on rotational strength and power to increase bat velocity. Additionally, sufficient swing practice increases bat velocity and should supplement resistance training (Szymanski et al., 2010).

Vision training, on the other hand, attempts to improve the sensory aspects of baseball batting linked to performance. As sensorimotor skills are essential in all sports, the efficacy of vision training has been analyzed as it relates to performance. There have been a number of instances across many sports where vision training has improved performance, however additional research is necessary to fully understand the impact that vision training can have (Knudson & Kluka, 1997; Khanal, 2015). A study to investigate this used visual training over a 4-week period and compared the performance in 17 different optometric, sport-specific perceptual, and sports-specific motor tests before and after the training period. The results showed no improvements occurred after training compared to the baseline performance (Wood & Abernethy, 1997).

While many studies are inconclusive on the impact vision training has on performance, there have been a number of studies that have shown vision training to improve performance in sports, including the hitting statistics of baseball players. Supporting this, improvements in visual skills occurred in collegiate baseball players during or after eight weeks of vision training using a Speesion software designed to improve visual functions compared to a control group (Kohmura & Yoshigi, 2004). Similarly, in 2008, the training effects the Vizual Edge software had on batting performance were evaluated in collegiate baseball players over a five-week training period. Results showed increases in batted-ball velocity as compared to the control group (Spaniol, Bonnette, Ocker, Melrose, & Paluseo., 2008). Comparable results have also been observed in tennis players as serve precision increased after eight weeks of vision training (Maman, Gaurang, & Sandhu, 2010). Supplementing this, the University of Cincinnati's baseball team completed 6 weeks of vision training, through various optometric methods, prior to the 2011 season and compared the results of the 2010 statistics to that of the 2011 season. Increases in team batting average by 34 points and slugging percentage by 33 points occurred while all other teams in the conference decreased performance; slugging percentage decreased by 82 points across other teams. All batting statistics analyzed increased by at least 10% (Clark, Ellis, Bench, Khoury, & Graman, 2012).

In today's game, it is a common strategy or goal of batters to maximize distance and strive for home runs. Thus, recent emphasis has been placed on batted-ball exit velocity and launch angle to maximize range trajectories (Szymanski, DeRenne, & Spaniol, 2009; Sawicki, Hubbard, & Stronge, 2003). While batted-ball launch angle is solely determined by the point of contact between the bat and ball, it can be improved through greater spatial accuracy provided by enhanced pitch tracking to better determine contact location. Batted-ball exit velocity is a result of the kinematics of the of the swing and can be improved through strength training to increase swing efficiency and generate greater power. With the limited success characteristic of batting, players are constantly looking for a competitive edge as 50 points on a batting average is equivalent to a salary in the millions. Therefore, it is important to develop effective training strategies identified from scientific research to improve performance.

Modalities for baseball swing measurements

The accuracy of measurement techniques to identify sensorimotor characteristics that relate to performance is important, especially when dealing with fractions of a second. Eye tracking glasses has become increasingly popular in recent years allowing researcher to analyze eye movements and gaze characteristics. Although these can be costly and possess inconvenient software that is not user-friendly, it can be used to examine the visual functions during athletic performances (Discombe & Cotterill, 2015). Eye tracking glasses can accurately measure eye movements and gaze vectors, and therefore gaze errors associated with tracking a target (Fogt &

Zimmerman, 2014). The use of dynamic areas of interest (AOI) within the eye tracking software to locate a target object allow for the calculation of gaze errors by comparing the gaze position vector to the area of interest (Papenmeier & Huff, 2010). Additionally, eye tracking software has the capability to detect saccadic movements, as well as smooth pursuit velocity in a reliable manner (Discombe & Cotterill, 2015; Versino et al., 1993).

It is also convenient that these eye tracking software are compatible with three-dimensional motion capture systems which allows for the analysis of both visual and body movements simultaneously. Motion capture systems are the primary method to measure kinematic data such as displacement and velocity. Numerous studies have accurately measure kinematic baseball swing data through high-speed motion capture systems in a reliable manner (Tabuchi, Matsuo, & Hashizume, 2007; Nakata, Mirua, Yoshie, Higuchi, Kudo, 2014; Inkster, Murphy, Bower, & Watsford, 2011, ; Fortenbaugh, Fleisig, Onar-Thomas, & Asfour, 2011, Takuo, Norihisa, Sekiya, & Mitsura, 2008).

Summary

Baseball batting research continues to identify factors that are indicative of skill level. Temporal analysis helps identify sensorimotor factors that influence performance. Training methods are developed from this to enhance these factors and improve batting performance. Increased decision time is an underlying idea behind improved performance from a sensory aspect (Szymanski et al., 2006; Szymanski et al., 2010). The decision time of a batter is directly related to the ability to track the pitch. A pitch that is tracked for a longer duration will provide more information on the trajectory of the ball to produce a more efficient action. A batter increases decision time through enhanced head and eye coordinative movements to track the ball later in its trajectory at higher velocities with reduced gaze errors. Alternatively, this can be accomplished by initiating tracking earlier in the pitch. From a motor standpoint, another underlying idea behind improved performance is decreasing the swing time (Szymanski et al., 2006; Szymanski et al., 2010). This can be accomplished through greater pelvis and bat kinematics. As traditional baseball batting research identifies sensory and motor aspects separately, bridging the gap between these components can help identify additional sensorimotor characteristics with the potential to develop more effective training strategies to improve performance.

Chapter III: Methods

Previous baseball research consists of experiments designed to either look at the sensory factors or the motor factors of hitting a baseball. After a thorough evaluation of previous research on this topic, it appears there have been no previous experiments designed to look at the relationship between the visual and motor components of the baseball swing. Additionally, research linking baseball swing kinematics as they correlate to pitch type is scarce and controversial.

Subjects

Sixteen male participants were recruited for this study. All participants had minimum playing experience at the high school level and were between the ages of 18 and 35 years old. The participants were recruited from both the collegiate student population, as well as individuals with collegiate varsity and club baseball experience. Both right-handed and left-handed batters were included in this study. All participants were heathy and free of any injuries at the time of data collection. The participants were divided into two groups classified as elite and sub-elite batters based on playing experience; the nine participants who had collegiate playing experience were categorized into the elite group, while the remaining seven participants with high school playing experience composed the sub-elite group. This study was approved by the University Institutional Review Board of East Carolina University. All participants were required to sign an informed consent of all testing procedures before data collection (see Appendix A). One participant was unable to complete to collection protocol due to insufficient skill level. Additionally, there was no eye and head data collected for one participant due to a malfunction of the eye tracking glasses; only pelvis and swing phase kinematics were measured.

Measurement protocol

Data collections consisted of a one-day protocol with each collection lasting approximately one hour. Participants were instructed to not engage in any physical activity on the day of testing prior to data collection. Data collections took place at Next Level Training Center (Greenville, NC) in a 60-foot batting cage (Figure 1). Upon arrival, participants answered a demographics questionnaire and signed an inform consent (see Appendix A). The participant then changed into spandex and motion capture markers were placed at anatomical landmarks using a custom marker set consisting of 71 total markers on the body, bat, and ball (see Table 1); a 12-camera Oqus Qualisys motion capture system (Qualisys AB, Gothenburg, Sweeden) was used to record kinematic data at 100hz. SMI Eye Tracking Glasses 2 Wireless ETG16-1026 (SensoMotoric Instruments, Boston, MA) recording at 120hz were secured on the subject before calibrating the body marker set. The calibration only markers were then removed and followed by five practice swings prior to calibrating the eye tracking glasses; eye tracking calibration was repeated after every five swings. Data collection consisted of 20 live pitches in three different conditions; five known fastballs, five known curveballs, and ten unknown mixed condition. As this study only included fastball trials, the curveballs were thrown to elicit a natural response to the unknown mixed condition. The same pitcher was used from a 40-foot distance for each participant and a radar gun was incorporated to ensure pitch velocity consistency within 3 mph for 45 mph fastballs and 40 mph curveballs. Quality of contact was recorded by both the participant and recorder after each swing using a Likert scale of zero to three, zero being a miss and three being solid contact.

Figure 1. Images from data collections at Next Level Training Center.

Table 1

Custom Marker Set for Motion Capture

Baseball Bat		Eye Tracking Glasses	
Marker Label	Marker Location	Marker Label	Marker Location
bat1	knob of bat	r.eye.ant	right eye tracker anterior
bat2	middle of bat proximal	r.eye.post	right eye tracker posterior
bat3	middle of bat distal	r.eye.inf	right eye tracker inferior
bat4	end of bat proximal	l.eye.ant	left eye tracker anterior
bat5	end of bat distal	l.eye.post	left eye tracker posterior
		l.eye.inf	left eye tracker inferior
Pelvis		**Torso**	
Marker Label	Marker Location	Marker Label	Marker Location
r.illcrest*	right illiac crest	jug	jugular notch
r.asis	right anterior superior iliac spine	c7	7th cervical spine vertebre
r.psis	right posterior superior iliac spine	r.scap	right scapula body
l.illcrest*	left illiac crest	r.scap.inf	right scapula inferior angle
l.asis	left anterior superior iliac spine	l.scap	left scapula body
l.psis	left posterior superior iliac spine	l.scap.inf	left scapula inferior angle
Right Arm		**Left Arm**	
Marker Label	Marker Location	Marker Label	Marker Location
r.ac	right acromioclavicular joint	l.ac	left acromioclavicular joint
r.gtub*	right greater tuberosity	l.gtub*	left greater tuberosity
r.ltub*	right lesser tuberosity	l.ltub*	left lesser tuberosity
r.hand	right hand	l.hand	left hand
r.wrist.med	right ulna styloid process	l.wrist.med*	left ulna styloid process
r.wrist.lat	right radius styloid process	l.wrist.lat	left radius styloid process
r.forearm.dist	right forearm distal tracker	l.forearm.dist	left forearm distal tracker
r.forearm.prox	right forearm proximal tracker	l.forearm.prox	left forearm proximal tracker
r.elbow.lat	right elbow lateral epicondyle	l.elbow.lat	left elbow lateral epicondyle
r.elbow.med*	right elbow medial epicondyle	l.elbow.med	left elbow medial epicondyle
r.arm.dist	right humerus distal tracker	l.arm.dist	left humerus distal tracker
r.arm.prox	right humerus proximal tracker	l.arm.prox	left humerus proximal tracker
Right Leg		**Left Leg**	
Marker Label	Marker Location	Marker Label	Marker Location
r.gtroch	right greater trochanter	l.gtroch	left greater trochanter
r.leg.ant	right thigh anterior tracker	l.leg.ant	left thigh anterior tracker
r.leg.post	right thigh posterior tracker	l.leg.post	left thigh posterior tracker
r.knee.med	right femur medial condyle	l.knee.med	left femur medial condyle
r.knee.lat	right femur lateral condyle	l.knee.lat	left femur lateral condyle
r.shank.prox	right shank proximal tracker	l.shank.prox	left shank proximal tracker
r.shank.dist	right shank distal tracker	l.shank.dist	left shank distal tracker
r.ankle.med	right medial malleolus	l.ankle.med	left medial malleolus
r.ankle.lat	right lateral malleolus	l.ankle.lat	left lateral malleolus
r.foot1	right 1st metatarsal distal	l.foot1	left 1st metatarsal distal
r.foot5	right 5th metatarsal distal	l.foot5	left 5th metatarsal distal
r.heel	right calcaneus	l.heel	left calcaneus

Note. * calibration only

Data processing

For each trial, the frames in which pitch release and contact occurred were determined visually from video data in Qualysis for analysis. Eye rotation was calculated from the eye position vectors exported from SMI BeGaze software. Eye rotation was calculated as the magnitude of eye displacement from pitch release to contact in the horizontal plane only; this value was divided by the pitch flight duration to obtain average angular velocity for each trial.

$$eye\ rotation = |eye\ displacement| \frac{degree}{60\ pixels}$$

$$average\ eye\ angular\ velocity = \frac{eye\ rotation}{(bat - ball\ contact\ frame - release\ frame)} * 120hz$$

Qualisys Track Manager was used to label the marker trajectories using a custom Automatic Identification of Markers (AIM) model (see Table 1), which automatically tracks labeled markers based on trajectory throughout each trial; determination of the swing duration and loading, landing, and launching phases were also accomplished through video analysis within Qualisys. To determine the load phase duration, the difference between frame when the batter began to shift his weight backward initiating the swing movement with regard to the hip marker and the frame when the load point occurred (the point at which the hip marker is furthest from the pitcher) was calculated and divided by the frame rate of 100 frames per second to determine the time in seconds. Similarly, the land phase duration was calculated from the difference between the load point frame and the frame when the front foot initially re-establishes contact with the ground, while the launch phase duration was calculated from the difference of the front foot contact frame and the bat-ball contact frame, and each were divided by the frame rate to determine the time in seconds. The load-release difference was calculated as the difference in time between the load point frame and pitch release frame by dividing by the frame rate (see Figure 2).

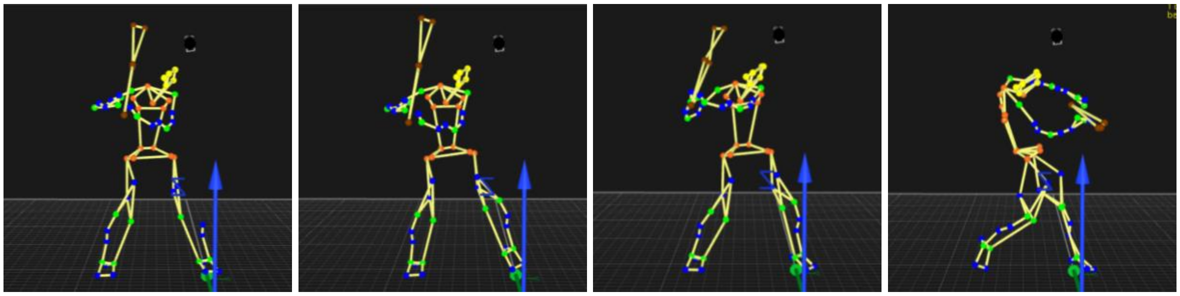

Figure 2. Example of the different swing phases (initiation, load point, land point, contact point).

$$load\ phase\ duration = (load\ point\ frame - swing\ initiation\ frame\ )/100hz$$

$$land\ phase\ duration = (land\ point\ frame - load\ point\ frame)/100hz$$

$$launch\ phase\ duration = (bat - ball\ contact\ frame - land\ point\ frame)/100hz$$

$$swing\ duration = load\ phase\ duration + land\ phase\ duration + launch\ phase\ duration$$

$$load - release\ difference = (load\ point\ frame - pitch\ release\ frame)/100hz$$

Marker trajectory data was exported to Visual3D (C-Motion Inc., Germantown, MD) where a model was built for the head and pelvis for kinematic analysis (Figure 3). The head model was built from the six markers on the eye tracking glasses. To define the proximal joint and radius the left and right inferior markers were used, while the left and right anterior markers were used to define the distal joint and radius. All six of the eye tracking markers were included as tracking markers to define the head segment. For the pelvis model, the proximal joint and radius was defined using the left and right iliac crest markers, while the left and right greater trochanter markers were used to define the distal joint and radius. The left and right ASIS and PSIS markers were used as tracking markers to define the pelvis segment. This model was used to determine head and pelvis angular positions at pitch release and bat-ball contact points, average head angular velocity from pitch release to bat-ball contact, peak pelvis angular velocity, and pelvis angular velocity at bat-ball contact using Euler's method of Cardan angles; head and pelvis data was exported and analysis included rotations, relative to the global coordinate system, around the vertical axis in the transverse plane only.

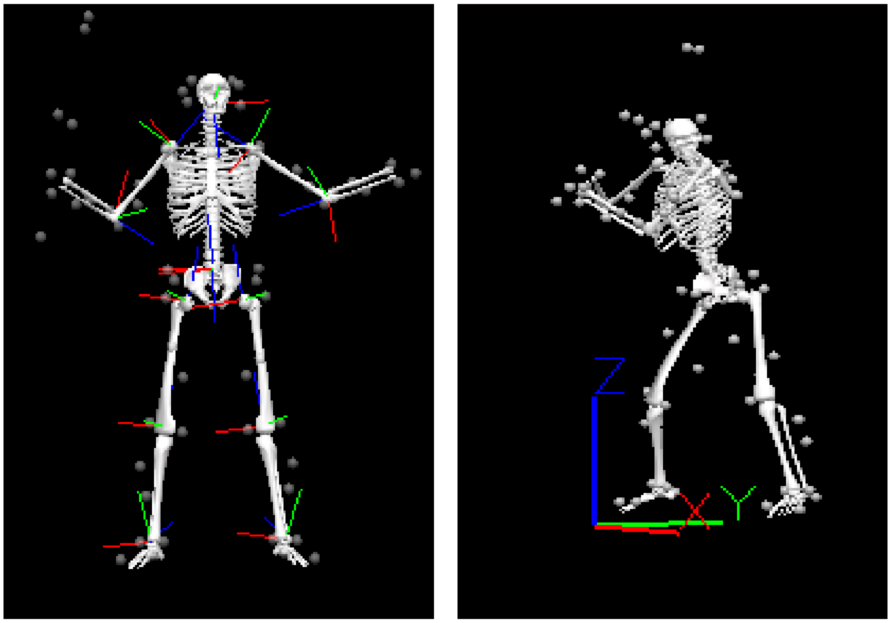

Figure 3. Image of the Visual3D skeletal model.

The bat-ball contact and pitch release points were determined for each trial in Qualisys Track Manager and entered in Visual3D as events within a pipeline that was built to calculate the following data. Head rotation was determined by the difference in angular position between the release and contact event points, while pelvis rotation was determined by the difference in angular position between the load and contact points. The peak pelvis angular velocity was the maximum instantaneous velocity exhibited by the batter between the release and contact events, whereas the pelvis angular velocity was the instantaneous velocity of the pelvis at the contact event point. Rotation data was calculated in degrees, velocity in degrees per second, and durations in seconds for each trial.

$$head\ rotation = head\ angular\ position\ at\ contact - head\ angular\ position\ at\ release$$

$$average\ head\ angular\ velocity = head\ rotation\ /\ (bat - ball\ contact\ frame - release\ frame) * 100hz$$

$$pelvis\ rotation = pelvis\ angular\ position\ at\ contact - pelvis\ angular\ position\ at\ load\ point$$

Statistical analysis

There were 12 total variables that were incorporated for statistical analysis; these consisted of eye rotation, average eye angular velocity, head rotation, average head angular velocity, pelvis rotation, peak pelvis angular velocity, pelvis angular velocity at contact, load phase duration, land phase duration, launch phase duration, total swing duration, and the load-release difference. Kinematic data was calculated for the fastball trials only, excluding the curveball trials, for analysis to examine the relationship between the sensory and motor aspects of hitting a baseball. The predictors, or independent variables, consisted of the sensory data provided from eye and head rotation. The criterion, or dependent variables, consisted of the motor data provided from the pelvis and swing phase kinematics. Regression analysis was used to determine a sensorimotor relationship for both the elite and sub-elite groups independently. Due to the multiple predictor and criterion variables, multivariate multiple regression was performed in a stepwise manner within SPSS V25 (IBM Corp., Armonk, NY).

Each kinematic variable was also averaged across fastball trials only, excluding the curveball trials, for both the known and unknown conditions for each participant, providing each participant with a known and unknown average for each kinematic measurement; this data was also categorized as elite or sub-elite for analysis. A two (skill level) by two (pitch type) repeated measures analysis of variance (ANOVA) was performed to determine statistically significant differences of this data with regards to pitch condition and skill level using SPSS.

Chapter IV: Results

Two-Way Repeated Measures ANOVA

Known vs. Unknown Comparison. The known versus unknown analysis revealed differences in head rotation, average head angular velocity, pelvis rotation, and load-release difference between the known and unknown pitch conditions (see Appendix B). No differences in eye rotation (p = 0.779) or average eye angular velocity (p = 0.898) was observed. Head rotation was greater (F(1, 12) = 12.186, p < 0.01) in the unknown condition (M = 22.35°) in comparison to known condition (M = 18.00°). Average head angular velocity was also greater in the unknown condition with an average of 28.05 degrees per second compared to 22.31 degrees per second in the known (F(1, 12) = 7.387, p = 0.019) (Figure 4a).

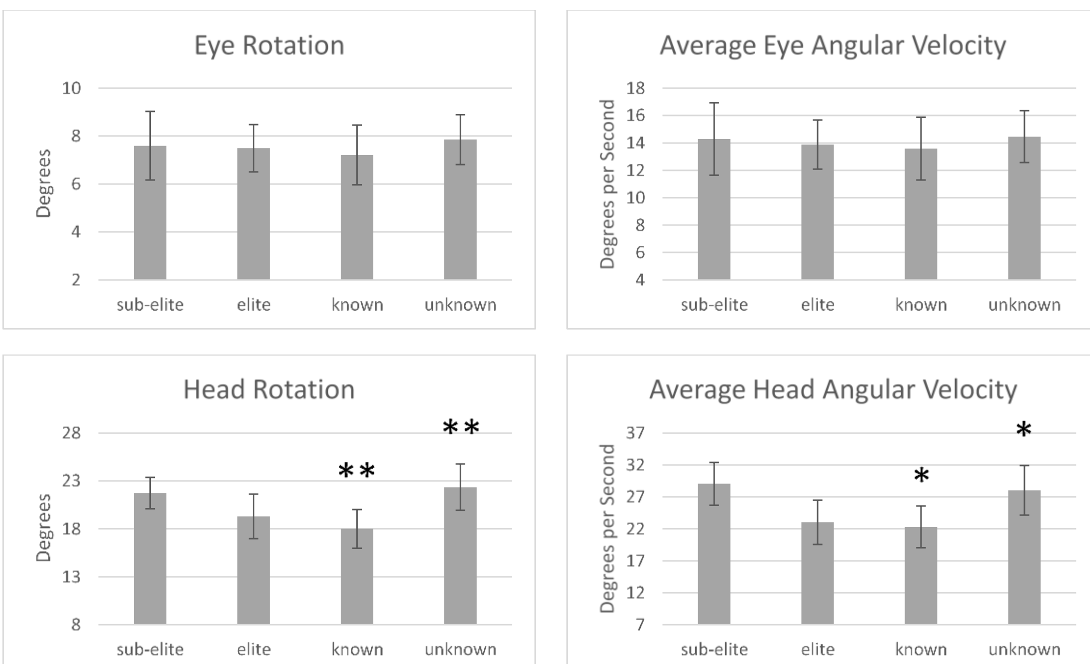

Figure 4a. Bar graphs of the averaged data from the ANOVA for eye and head kinematics (*p < 0.05, **p < 0.01).

Pelvis rotation was smaller ($F(1, 13) = 12.447$, $p < 0.01$) in the unknown condition (M = 85.65°) in comparison to known condition (M = 89.61°) (Figure 4b). No differences in peak pelvis angular velocity ($p = 0.112$), pelvis angular velocity at contact ($p = 0.413$), the load phase ($p = 0.355$), land phase ($p = 0.681$), launch phase ($p = 0.182$), and total swing durations ($p = 0.257$) between the known and unknown conditions were found.

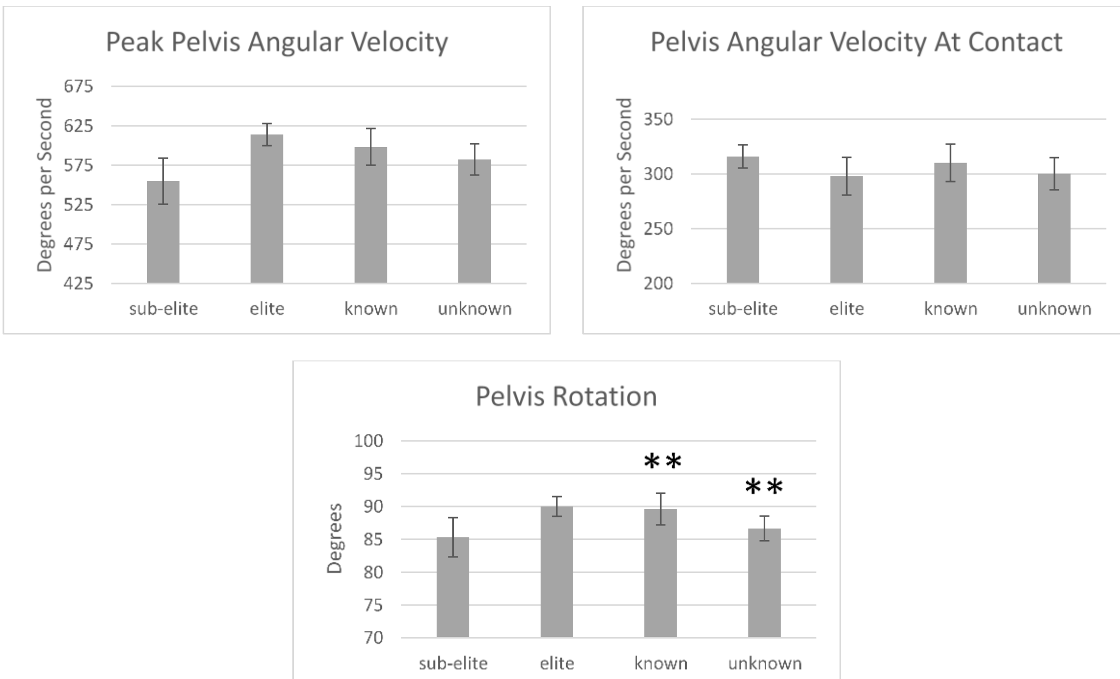

Figure 4b. Bar graphs of the averaged data from the ANOVA for pelvis kinematics (*$p < 0.05$, **$p < 0.01$).

Elite vs. Sub-Elite Comparison. The elite versus sub-elite analysis revealed differences in the load phase duration, land phase duration, total swing duration, and load-release difference between the elite and sub-elite groups (see Appendix B). No differences in eye rotation ($p = 0.960$), average eye angular velocity ($p = 0.913$), head rotation ($p = 0.610$), average head angular velocity ($p = 0.426$), pelvis rotation ($p = 0.297$), peak pelvis angular velocity ($p = 0.181$), and pelvis angular velocity at contact ($p = 0.579$) were observed. The load phase duration was greater in the elite group with 0.615 seconds on average from the initial loading movement compared to 0.421 seconds in the sub-elite group ($F(1, 13) = 8.397$, $p = 0.012$). The land phase duration was greater in the elite group with 0.406 seconds on average compared to 0.269 seconds in the sub-elite group ($F(1, 13) = 7.709$, $p = 0.016$). No differences in the launch phase duration ($p = 0.873$) were found. Total swing durations were greater ($F(1, 13) = 11.227$, $p < 0.01$) in the elite group with (M = 1.265 sec) compared to the sub-elite group (M = 0.942 sec) (Figure 4c).

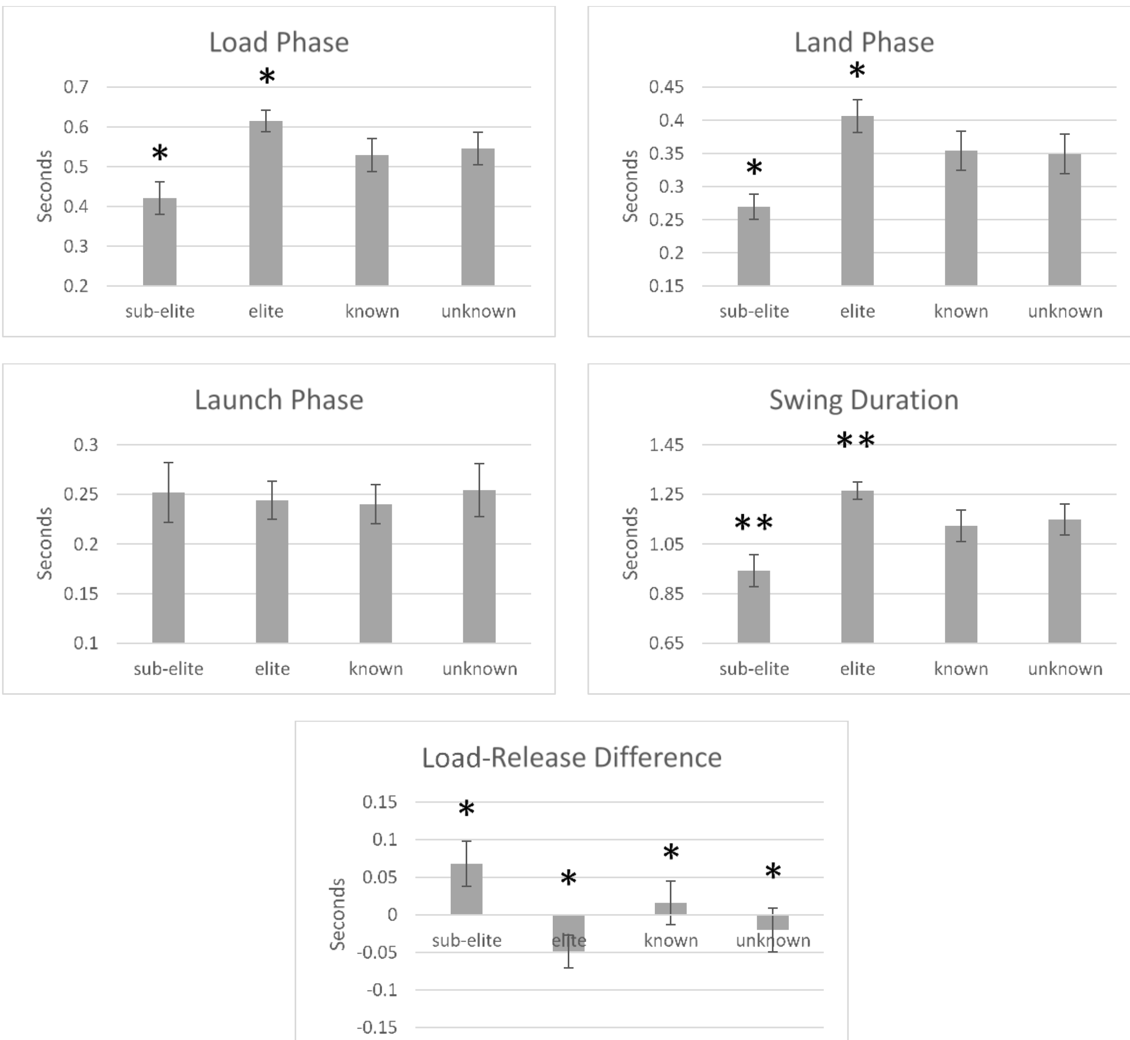

Figure 4c. Bar graphs of the averaged data from the ANOVA for swing phase kinematics (*$p < 0.05$, **$p < 0.01$).

Both the known versus unknown and elite versus sub-elite comparisons show differences in the load-release difference. The load-release difference occurred earlier, prior to the pitch release, in the unknown condition at -0.020 seconds on average compared to 0.016 seconds after the pitch release in the known ($F(1, 13) = 7.840$, $p = 0.015$). The load-release difference also occurred earlier, prior to the pitch release, in the elite group at -0.049 seconds on average compared to 0.068 seconds after the pitch release in the known ($F(1, 13) = 5.276$, $p = 0.039$) (Figure 4c).

Interaction Results. There was a significant interaction between the effects of pitch type and skill level on pelvis rotation $F(1, 13) = 9.344$, $p = 0.009$. The elite group exhibited greater pelvis rotation in the known condition with 92.4 degrees compared to the unknown condition of 87.6. This was not observed in the sub-elite group with 85.5 and 85.2 for the known and unknown conditions, respectively (Figure 5).

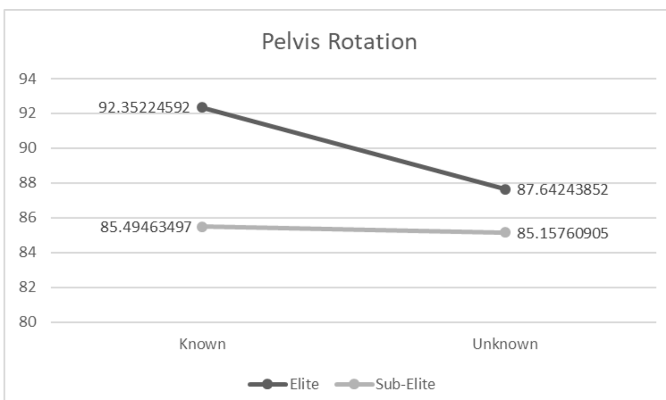

Figure 5. Interaction plot of pelvis rotation.

Multivariate Multiple Regression

Elite Regression Analysis. A multivariate multiple regression was run to predict pelvis and swing phase kinematics from eye and head rotation for the elite and sub-elite groups independently. While the analysis for the elite group revealed no relationships between eye rotation and peak pelvis angular velocity (p = 0.448), pelvis angular velocity at contact (p = 0.518), the load phase duration (p = 0.786), the total swing duration (p = 0.766), or the load-release difference (p =0.974), this study demonstrated a positive correlation between eye rotation with pelvis rotation, $F(1, 81) = 6.147$, $p = 0.015$, $R^2 = 0.071$ (Figure 6a).

Both eye and head rotation were predictive of the land and launch phase durations in the elite group (see Appendix B). Greater eye rotation with less head rotation correlated with a shorter launch phase, $F(2, 80) = 6.687$, $p < 0.01$, $R^2 = 0.143$, while greater eye rotation with less head rotation correlated with a longer land phase, $F(2, 80) = 10.896$, $p < 0.01$, $R^2 = 0.214$. Both eye and head rotation also added to the prediction of the land phase duration independently, however only eye rotation predicted launch phase durations independently, $p < 0.05$; head rotation was not independently significant (p = 0.243) (Figure 6a).

Head rotations in the elite group were predictive of peak pelvis angular velocity and the load-release difference. Smaller head rotations correlated with greater peak pelvis angular velocities, $F(1, 81) = 15.887$, $p < 0.01$, $R^2 = 0.164$, and a smaller load-release difference $F(1, 81) = 6.546$, $p = 0.012$, $R^2 = 0.075$ (Figure 6a). However, no relationships between head rotation and pelvis rotation (p = 0.686), pelvis angular velocity at contact (p = 0.086), the load phase duration (p = 0.132), or total swing duration (p = 0.786) were observed.

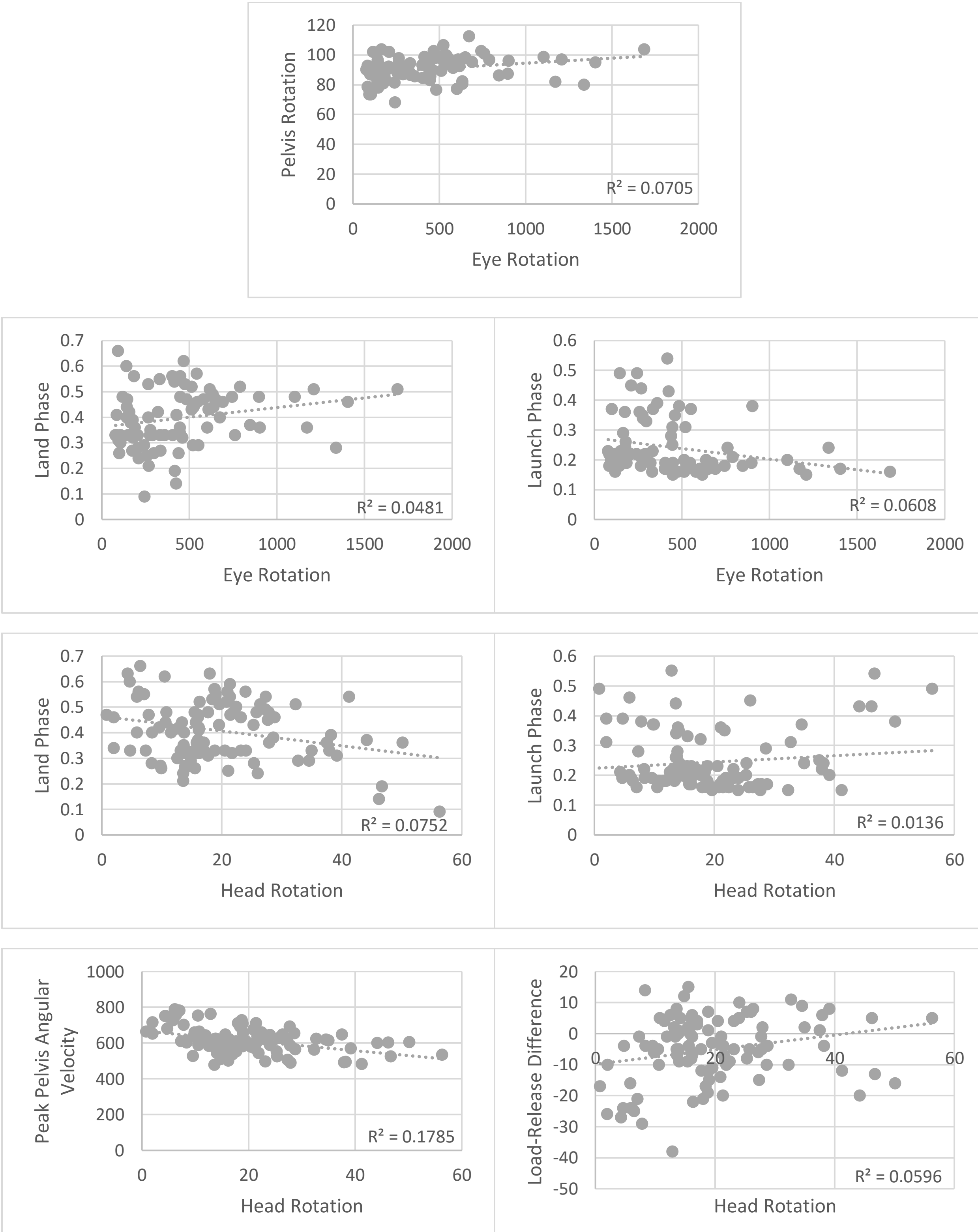

Figure 6a. Scatter plots from the regression analysis for the kinematic variables in which a relationship was found in the elite group.

Sub-elite Regression Analysis. In the sub-elite group, while a relationship was not observed between eye rotations and peak pelvis angular velocity (p = 0.088), pelvis angular velocity at contact (p = 0.930), the land phase duration (p = 0.290), launch phase duration (p = 0.532), total swing duration (p = 0.302), or the load release difference (p = 0.916), both eye and head rotations were predictive of pelvis rotation and the load phase duration. Smaller eye and head rotations correlated with greater pelvis rotation, $F(2, 64) = 18.029$, $p < 0.01$, $R^2 = 0.360$. However, only head rotation added to the prediction of the pelvis rotation independently, $p < 0.05$; eye rotation was not independently significant (p = 0.066). A positive relationship was observed between eye and head rotations with the load phase duration, $F(2, 64) = 5.966$, $p < 0.01$, $R^2 = 0.157$. Both eye and head rotation also added to the prediction of the load phase durations independently, $p < 0.05$ (see Appendix B) (Figure 6b).

Head rotations in the sub-elite group were predictive of peak pelvis angular velocity, pelvis angular velocity at contact, the land phase duration, total swing duration, and the load-release difference. Smaller head rotations were correlative of greater peak pelvis angular velocity, $F(1, 65) = 6.856$, $p = 0.011$, $R^2 = 0.095$, and greater pelvis angular velocity at contact, $F(1, 65) = 4.873$, $p = 0.031$, $R^2 = 0.070$. Greater head rotations showed a relationship with a longer land phase duration, $F(1, 65) = 8.142$, $p < 0.01$, $R^2 = 0.111$, longer total swing duration, $F(1, 65) = 11.147$, $p < 0.01$, $R^2 = 0.146$, and smaller load-release difference, $F(1, 65) = 10.216$, $p < 0.01$, $R^2 = 0.136$ (Figure 6b). However, no relationship between head rotation and the launch phase (p = 0.272) was observed.

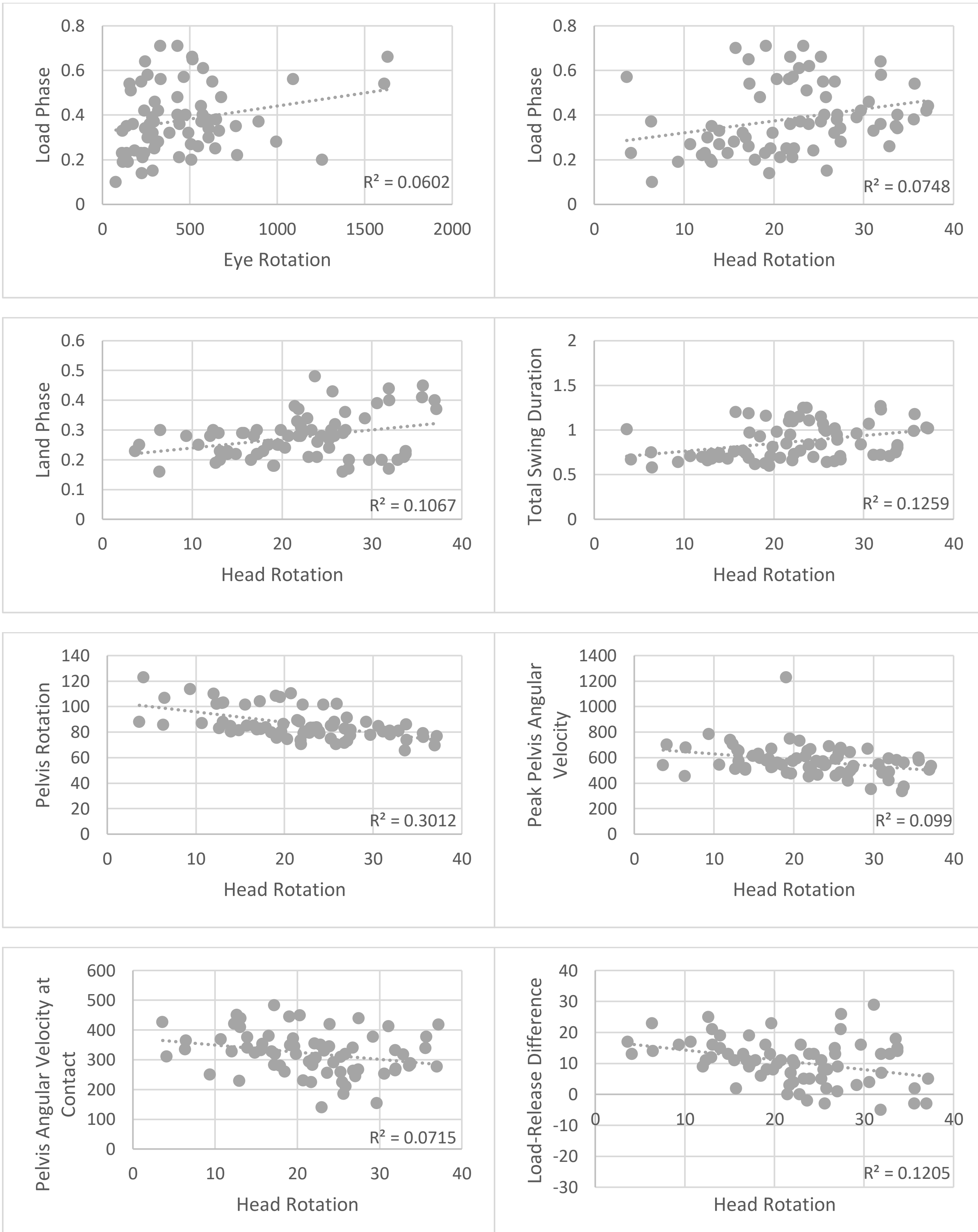

Figure 6b. Scatter plots from the regression analysis for the kinematic variables in which a relationship was found in the sub-elite group.

Quality of Contact

The frequency of quality of contact was calculated for each level with the known and unknown conditions, as well as the elite and sub-elite groups independently. The results showed that elites in the known condition produced higher quality of contact with 76% of the contacts rated a two or three, and 70% in the unknown condition. Similarly, the sub-elites produced higher quality of contact in the known condition with 58% of the contacts rated two or three, and 53% in the unknown condition. Overall, elites produced a higher ratio of quality of contact rated a two or three.

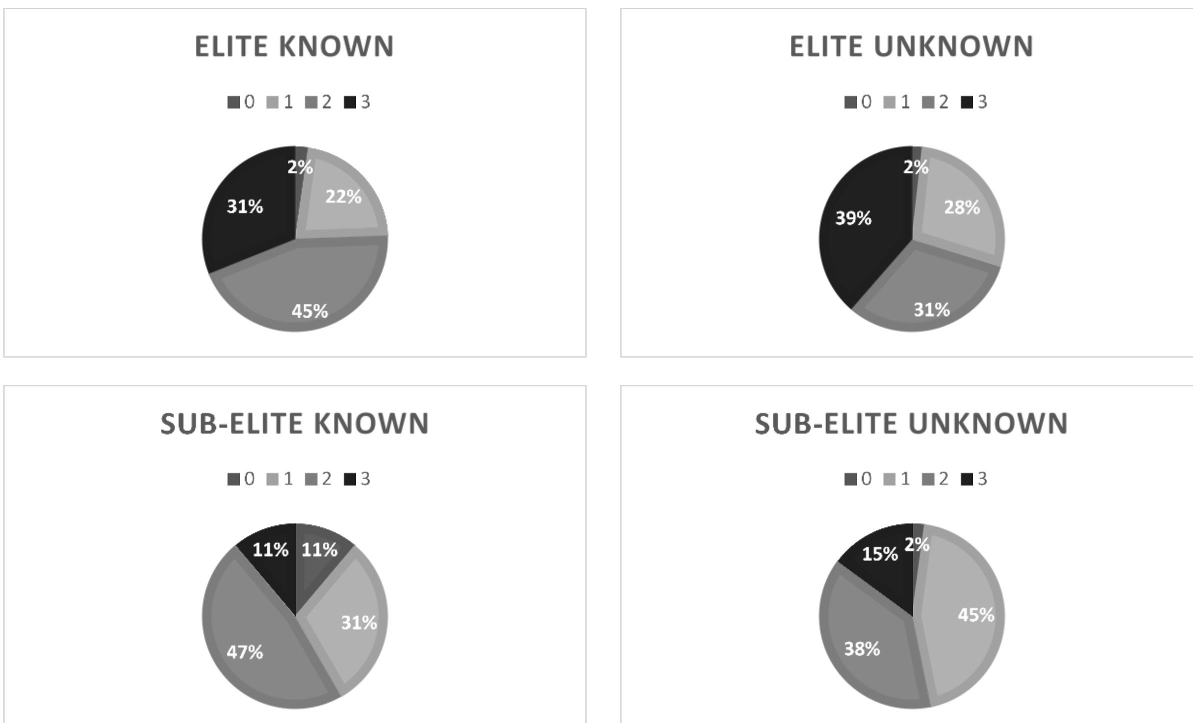

Figure 7. Pie charts of quality of contact frequencies.

Chapter V: Discussion

This is the first study that examined the sensorimotor kinematic changes of the baseball swing as a result of alterations in the response process across the same pitch type with skill level. Similar research has looked at alterations of a known and unknown pitch condition but lacked the factor of skill level and did not incorporate visual kinematic measurements in the analysis (Miaynishi & Endo, 2016; Takuo, Norihisa, Sekiya, & Mitsura, 2008). Additionally, this is the first known study to examine correlations between sensory and motor kinematics while hitting a baseball.

Greater quality of contact appears to occur when the pitch is known as compared to the unknown pitch condition, as well as with the elite group over the sub-elite group. Therefore, it seems that sensorimotor kinematics associated with the known pitch type provide an advantage for the hitter and allows for a more successful swing. As a result, those characteristics exhibited by the elite group and during the known pitch condition are likely the model in which training modalities should strive to replicate.

Sensory Implications

The results demonstrated that the head rotates more during the unknown condition as compared to the known. The increase in head rotation is likely to be compensatory as a result of the increase in required reaction time for success in the more complex sensorimotor condition. The head would likely rotate more to increase the pitch tracking duration, enhancing the visual processing of the pitch in an attempt to determine its unknown spatial and temporal properties. The increase in head rotation is also explanatory of the increase in average head angular velocity in the unknown condition; the response times were similar due to the inclusion of only fastballs, therefore if the head rotates more, the average head angular velocity is expected to increase as well. However, this same phenomenon was not observed in the amount of eye rotation, nor the average eye angular velocity, that occurs between the two conditions. It is suggested that head movement is the compensatory mechanism with response process alterations while the eyes move more consistently with regard to both skill level and pitch condition. The observed eye movement consistency contradicts the previous notions that faster eye movements and shorter latencies allow baseball players increased success with hitting a baseball (Uchida et al., 2013; Uchida et al., 2012).

Motor Implications

As hypothesized, pelvis rotation was greater in the known condition in comparison to the unknown condition. The advantage of knowing the temporal information of the pitch is that it potentially allows the batter more time to maximize the rotation of the pelvis in response to less time dedicated to visual processing of the pitch. Based on the findings from the classic study by Donders, along with similar results found by Miller and Low, the motor time is constant regardless of task complexity while the reaction time is responsible for the increase in response times (Donders, 1969; Miller & Low, 2001).

This is supported by the current study as the launch phase, represented by the rotational motion of the swing, remained unaltered across the different response conditions, while the load and land phases increased. Therefore, to maintain the swing movement time while exhibiting greater rotation, the angular velocities must also be increased. It would be expected for peak pelvis angular velocity to be greater in the known condition, however this was not demonstrated by the results. The peak rotational velocities of the pelvis may be more characteristic of a batter, representative of strength or mechanics, as there were no differences in peak pelvis angular velocity or pelvis angular velocity at contact between the two conditions. Additional research should be done to analyze when peak pelvis angular velocity occurred during the swing sequence to determine if there are any trends exhibited with altering the pitch condition or skill level.

Attributing rotational velocities of the swing to prior experiences is supported by the schema theory that indicates the movement time associated with complex movements can be reduced with sensorimotor coordination facilitated through practice (Schmidt, 1975; Light, Reilly, Behrman, & Spirduso, 1996). The schema theory implies that discrete movements are dictated by accumulated experiences which facilitate decision making through memory (Schmidt, 1975). This theory suggests that prior batting practice in a realistic scenario to refine the recall schema can help a batter improve the swing movement, which in turn guides future attempts. With sufficient practice, movements such as hitting a baseball can become an especial motor skill through the schema theory (Keetch, Schmidt, Lee, & Young, 2005). The schema theory was used to display such especial motor skill development in baseball context as experienced pitchers showed more accuracy throwing from regulation distances as opposed to shortened and lengthened distances (Simons, Wilson, Wilson, and Theall, 2009).

The results also revealed an interaction between skill level and pelvis rotation for pitch condition. The elite group exhibited greater rotation of the pelvis in the known condition in comparison with the unknown, although this was not observed in the sub-elite group as rotation remained constant across both conditions. However, as previously mentioned, pelvis rotation was greater in the known condition as compared to the unknown across all participants in this study; this difference can be attributed to alterations in the elite group alone. This suggests that pelvis rotation is indicative of skill level and increased success, supporting previous literature (Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014; Inkster, Murphy, Bower, & Watsford, 2011). However, pelvis rotation did not exhibit any trends as to if this increase was due to a greater loading rotational movement or a greater rotational movement during the launch phase. The increase in pelvis rotation seems to be more likely related to the individual swing strategies exhibited on a player to player basis.

Temporal Implications

As a timing mechanism, the batter appears to synchronize the load point with the release point of the pitcher, indicating that the load phase is in response to the pitcher's wind up. The load-release difference is also affected by task complexity. This study demonstrated that the load point occurred before the pitch release in the unknown condition, while in the known condition batters reached that point after the release point. Similar to head rotation, this is likely compensatory as an attempt to allow the batter more time to be allocated for the land phase, as the launch phase duration remains consistent. The load-release difference was also affected by skill level. This study demonstrated that the elite group reached the load point before the pitch release, while this occurred after the pitch release for the sub-elite group. It can be inferred that shifting the weight back sooner in the swing process to reach the load point earlier, just prior to pitch release, is advantageous to success while hitting a baseball.

It was hypothesized that the longer the pitch can be tracked visually, a more accurate and powerful swing can be produced. The batter visually tracks the pitch to determine its spatial and temporal properties to decide how to and whether or not to swing. The load and land phase will occur in both the take condition, during which a batter decides not to swing, as well as the swing condition to achieve the task of hitting a baseball. The difference is in the launch phase which only occurs in the swing condition to produce the actual swing movement. As the load phase is in response to the pitcher's windup until the load point occurs at pitch release, the land phase occurs during the pitch flight when the pitch tracking occurs. Once the decision is made to swing, the launch phase follows as the swing motion is initiated when the front foot reestablishes ground contact at the end of the land phase (Nakata et al., 2013; Miyanishi & Endo, 2016; Shaffer, Jobe, Pink, & Perry, 1993; Messier & Owen, 1985). From this, it can be concluded that the reaction time, associated with determining spatial and temporal characteristics while tracking the pitch during flight, is simultaneous to the land phase to influence the movement of the swing during the launch phase. Therefore, it seems advantageous for a longer land phase duration to enhance pitch tracking, achieved by reaching to load point earlier.

Supportively, the load and land phase durations were affected by skill level. The elite group exhibited longer load and land phase durations than their sub-elite counterparts. As previously mentioned, these phases occur simultaneously to visually tracking the pitch. Therefore, increasing these durations allows for more time to determine the pitch characteristics and increase success. As the launch phase remains consistent across skill level, the elite group begins their response earlier in reaction to the pitcher's windup to accommodate for these increased load and land phase durations. As a result, the total swing durations were greater in the elite group as opposed to the sub-elite batters.

Sensorimotor Implications

With regard to the impact of sensory kinematics on motor kinematics, this study demonstrated that less head rotation for both the elite and sub-elite groups were predictive of greater peak pelvis angular velocity which skilled batters have exhibited (Inkster, Murphy, Bower, & Watsford, 2011; Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014). The elite group displayed that the rotation of the eyes and the head are predictive of the launch phase duration, during which the swing motion occurs. As eye rotation decreases and head rotation increases, the launch phase duration increases. Previous research indicates that quicker swing motions, producing a shorter launch phase, are indicative of skill level and increased success; enhanced eye rotations have also been linked to skill level (Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014; Inkster, Murphy, Bower, & Watsford, 2011; Uchida et al., 2013; Uchida et al., 2012). A similar phenomena was demonstrated for greater pelvis rotations indicative of skill (Nakata, Miura, Yoshie, Higuchi, & Kudo, 2014). This further implies that head rotation increases are disadvantageous to success with hitting a baseball. However, as the head and pelvis rotates during the same time in the swing sequence, perhaps limiting the head rotation simply allows for greater pelvis rotation to occur as these rotations are in the opposite direction of one another. Additional research should be concluded to examine this relationship further.

A relationship opposite to that of head and eye rotation with the launch phase was observed with the land phase in the elite group. Increasing the land phase duration, which is advantageous to hitters, is associated with smaller head rotation and greater eye rotation, again supporting the idea of enhanced eye rotation with limitations on head rotation being indicative of skill. However, the land phase duration showed a positive association with the sub-elite group head rotation; additionally, the load-release difference was positively associated with head rotation of elites while negatively associated with sub-elites. The differences displayed between the groups with the land phase duration and load-release difference may be explanatory of the differentiation of skill level. While the head and eye rotations seem to work inversely of each other, the sub-elite group demonstrated positive correlations with both head and eye rotation with the load phase. This could potentially be explanatory of inferior sensorimotor coordination shown in novices (Bayhill & LaRitz, 1984; Hubbard & Seng, 1954; Uchida, Kudoh, Higuchi, & Kanosue, 2013; Uchida Kudoh, Murakami, Honda, & Kitazawa, 2012). It is important to note that all relationships displayed only weak to moderate correlations and R^2 values, as shown in Table 4 (see Appendix B).

Practical Implications

The information provided in this study can potentially help shape training modalities to improve performance. From a temporal standpoint, training a batter to initiate their load phase movement earlier in the pitcher's windup and to reach the load point prior to the release of the pitch seems to benefit the batter. According to the findings of this study, training should emphasize controlled landing phase movements to increase the duration and allow for a more accurate swing. Supported by previous research, training should also aim to maximize the rotational kinematics of the pelvis to increase the energy transferred from the body to the baseball, as well as to reduce the required movement time allowing for more time to be allocated to pitch reaction. An emphasis on the kinematics of the head and the eyes seems warranted through training modalities as well. Vision training has the potential to enhance the eye movements that occur, requiring less compensatory head movements; training to improve pitch recognition can assist in limiting head rotations and maximize the pelvis kinematics to increase success. Sufficient practice has been shown to reduce the effects of Hick's Law, allowing for a more efficient response with an increase in possible choices, or in this case possible pitch types, through decreased reaction times (Mowbray & Rhoades, 1959). Due to a greater quality of contact observed in the known pitch condition, it appears that training kinematic alterations associated with the unknown swing to mimic the mechanics during the known condition could be a viable strategy. Additional research is necessary to determine what training strategies can facilitate such changes to improve the success of batting, as well as to fully understand the relationships between the sensory and motor components while hitting a baseball.

Limitations and Future Recommendations

There were some limitations associated with this study. The sample size presents a limitation to this study as there were only sixteen participants recruited, resulting in only seven and nine subjects for the sub-elite and elite groups respectively. Although participants were categorized based on playing experience, there still exists skill variability within the two groups. Despite the fact the same pitcher was used with all participants, disparity in the pitches occurred. Additionally, the collection environment presented challenges to the ability of motion capture system tracking the bat throughout each trial to incorporate bat velocity, and the eye tracking glasses limited the field of view for batters while tracking the pitch. Controlling for certain factors this study utilized a shortened pitching distance and an indoor batting cage environment which may not accurately simulate a live game scenario. Therefore, future research should incorporate an on-field setting to accurately mimic the task.

The method for which eye rotations were calculated neglected direction. Analyzing eye rotations more accurately can help to shed light on the interactions between sensory and motor characteristics; a more in-depth analysis with the determination of smooth pursuit velocities and saccadic eye movements is required. Relatively, this study did not include gaze error between the gaze vector position and the ball location during the pitch flight. This could potentially provide a more thorough description of the connection between sensory and motor components of the baseball swing. Additional improvements could be made through the synchronization of the eye tracking glasses with the motion capture system instead of analyzing eye movements independently and recording motion capture data at a higher frame rate can potentially provide more accurate data. This study also only measured horizontal rotational data in the transverse plane; measuring rotation in all planes can provide more accurate data as well.

Correlating quality of contact with swing kinematics, which is the ultimate goal of the task, seems to be a direction for future research and can also help determine characteristics indicative of success; it is possible to achieve this by measuring exit velocity and incorporating technologies such as Rapsodo. To build on the findings of this research study, incorporating additional pitch types and including kinematic analysis of the torso and bat, as well as the kinetics associated with the ground reaction forces produced, would likely provide a more complete understanding of skilled batting and the relationship between the sensory and motor aspects of hitting a baseball. The relationships between head rotation and the land phase duration and load-release difference is another factor to be examined next to explain why opposite relationships were observed with skill level in this study. The next step in analyzing the phenomenon associated with pitch types leads to the utilization of simulations through virtual environments. Virtual reality systems are potentially a viable option to help train batters in pitch recognition with regards to observing a pitcher's arm motions, release points, and ball trajectories. Additionally, developing training modalities that correlate to enhanced kinematics indicative of increased performance observed in this study is another path future research can follow to build on this study.

Conclusions

As previously mentioned, pitchers appear to be dominating the game statistically by exploiting the choice reaction time increase via a greater variety of pitch types in their arsenal. The goal of training should be to limit the required reaction time for success by training to enhance the sensory components of the swing process. Overall, this study demonstrated kinematic differences associated with the baseball swing as a result of skill level and the complexity of the sensorimotor response task. Training to extend the pitch tracking duration to limit spatial and temporal inaccuracies, and to maximize rotational kinematics for a quicker swing movement, can potentially improve performance. Initiating the swing and reaching the load point earlier, as well as limiting head rotation and maximizing pelvis rotation, has been shown to be advantageous to the hitter. Additional research is needed to provide a more thorough understanding of the relationship between sensory and motor kinematics, as well as to develop effective training methods that improve these swing qualities which are indicative of skill level and success rates, limited by the choice response phenomena, in a game currently dominated by pitching.

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APPENDIX A: DATA COLLECTION DOCUMENTS

East Carolina University

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Kinematic Analysis of the Baseball Swing with Pitch Type and Skill Level
Principal Investigator: Ryan Silberg
Institution/Department or Division: Kinesiology
Address: 332 Ward Sports Medicine Building, East Carolina University
Telephone #: 252-737-4616

Researchers at East Carolina University (ECU) study problems in society, health problems, environmental problems, behavior problems and the human condition. Our goal is to try to find ways to improve the lives of you and others. To do this, we need the help of volunteers who are willing to take part in research.

Why is this research being done?
The purpose of this study is to evaluate the kinetics, kinematics and visual biomechanics of the baseball and softball swings in four separate training conditions in a population of healthy young adults who are current or former baseball or softball players. The decision to take part in this research is yours to make. By doing this research, we hope to learn more about the kinetics and kinematics of the baseball and softball swings in different practice conditions.

Why am I being invited to take part in this research?
You are being invited to take part in this research because you meet the inclusion criteria and appear to be free of contraindications to participating in this study. Inclusion criteria for this study are: being between ages 18-35, played competitive baseball or softball at or after the age of 16, and being recreationally active.

Are there reasons I should not take part in this research?
I understand that I should not take part in this research if I am not between the ages of 18 and 35 years old, generally healthy, or recreationally active.

What other choices do I have if I do not take part in this research?
You can choose not to participate.

Where is the research going to take place and how long will it last?
The research procedures will be conducted at Next Level Training Center, 1750 Wimbledon Dr, Greenville, NC 27858. You will need to come to Next Level Training Center once for approximately two hours, including the completion of this Informed Consent Form.

What will I be asked to do?
You are being asked to do the following:

1. Have your height and weight measured.
2. Provide demographic information.

What possible harms or discomforts might I experience if I take part in the research?
It has been determined that the risks associated with this research are no more than what you would experience in everyday life. You should not experience any discomfort from any aspect of this study. If you do experience discomfort please inform the study staff.

What are the possible benefits I may experience from taking part in this research?
We do not know if you will get any benefits by taking part in this study. This research might help us learn more about how similar baseball or softball swings are in different training conditions. There may be no personal benefit from your participation but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?
We will not be able to pay you for the time you volunteer while being in this study.

What will it cost me to take part in this research?
It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?
To do this research, ECU and the people listed below may know that you took part in this research and may see information about you. With your permission, these people may use your private information to do this research:

- Any agency of the federal, state, or local government that regulates human research. This includes the Department of Health and Human Services (DHHS), the North Carolina Department of Health, and the Office for Human Research Protections.
- The University & Medical Center Institutional Review Board (UMCIRB) and its staff, who have responsibility for overseeing your welfare during this research, and other ECU staff who oversee this research.
- Christopher Curran, the primary investigator, Zac Domire, the faculty supervisor, and sub-investigators Patrick Rider, Nick Murray, Nate Harris, and Ryan Silberg.

How will you keep the information you collect about me secure? How long will you keep it?
Data files will be kept for 5 years after the study is completed. The investigators will keep your personal data in strict confidence by having your data coded. Instead of your name, you will be identified in the data records with an identity number. Your name and code number will not be identified in any subsequent report or publication. The main investigator and the research students will be the only persons who know the code associated with your name and this code as well as your data will be kept in strict confidence. The computer file that matches your name with the ID number will be encrypted and the main investigators will be the only staff that knows the password to this file. The data will be used for research purposes.

What if I decide I do not want to continue in this research?
If you decide you no longer want to be in this research after it has already started, you may stop at any time. You will not be penalized or criticized for stopping. You will not lose any benefits that you should normally receive.

Who should I contact if I have questions?
The people conducting this study will be available to answer any questions concerning this research, now or in the future. You may contact the Faculty Coordinator, Zac Domire at 252-737-4564 (work days between 8am and 5pm) or the principal investigator, Christopher Curran at 252-737-4616 (work days, between 8am and 5pm).

If you have questions about your rights as someone taking part in research, you may call the Office for Research Integrity & Compliance (ORIC) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director of the ORIC, at 252-744-1971.

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

____

Participant's Name (PRINT) **Signature** **Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

____

Person Obtaining Consent (PRINT) **Signature** **Date**

Participant Demographics

Sub #:	Date:	Collector:

BASEBALL / SOFTBALL

Height (m):	
Mass (kg):	
Age:	
Vision Prescription:	
Floor to ASIS:	
Floor to Lat Epicondyle of Knee:	
Mid Thigh Height (tee height)	
When was your last season of competitive play?	Fall / Spring ________
How many years did you play competitively?	
What was the highest level that you competed at for school?	
What was the highest level that you played at outside of school?	
What level were you playing at when you stopped playing?	
How many months/year did you play at your highest level?	
What was your primary position when you stopped playing?	
What was your batting average during your last competitive season?	

BBSB Swing Collection Notes

SubID:____________ **Date:______________** **Collector:_________**

Mocap Notes: (marker replacement, bad trials, QTM notes, etc.)

Eye-Tracker Notes: (errors, use of phone, etc.)

RECALIBRATIONS

Added into AIM Model

Static_Cal	
Dynamic_Cal	

Static_NoCal	
Dynamic_NoCal	

Tee	
PopTee	
SoftToss	

APPENDIX B: STATISTICAL ANALYSES TABLES

Table 2

Descriptive Statistics

Kinematic Variable	Known		Unknown	
	Mean	*SD*	*Mean*	*SD*
Eye Rotation (deg)	7.212	4.656	7.853	3.903
Average Eye Angular Velocity (deg/s)	13.585	8.586	14.463	7.076
Head Rotation (deg)	18.005	7.539	22.346	9.031
Average Head Angular Velocity (deg/s)	22.308	12.195	28.053	14.521
Pelvis Rotation (deg)	89.609	9.363	86.648	7.265
Peak Pelvis Angular Velocity (deg/s)	598.228	90.174	582.326	76.784
Pelvis Angular Velocity at Contact (deg/s)	310.185	66.093	300.196	57.397
Load Phase (s)	0.529	0.161	0.546	0.159
Land Phase (s)	0.354	0.114	0.349	0.116
Launch Phase (s)	0.24	0.076	0.254	0.103
Total Swing (s)	1.123	0.247	1.149	0.24
Load-Release Difference (s)	0.016	0.112	-0.02	0.113

Kinematic Variable	Elite		Sub-Elite	
	Mean	*SD*	*Mean*	*SD*
Eye Rotation (deg)	7.495	4.182	7.598	4.539
Average Eye Angular Velocity (deg/s)	13.877	7.601	14.289	8.374
Head Rotation (deg)	19.312	9.854	21.729	5.191
Average Head Angular Velocity (deg/s)	23.03	14.67	29.05	10.616
Pelvis Rotation (deg)	89.997	6.381	85.326	10.37
Peak Pelvis Angular Velocity (deg/s)	613.944	59.468	554.778	101.332
Pelvis Angular Velocity at Contact (deg/s)	297.996	73.1	315.983	36.75
Load Phase (s)	0.615	0.115	0.421	0.142
Land Phase (s)	0.406	0.105	0.269	0.066
Launch Phase (s)	0.243	0.081	0.251	0.104
Total Swing (s)	1.265	0.147	0.942	0.223
Load-Release Difference (s)	-0.049	0.093	0.068	0.104

Table 3

Two-Way Repeated Measures ANOVA

Known vs. Unknown					
Kinematic Variable	*Sum of Squares*	*df*	*Mean Square*	*F*	*p-value*
Eye Rotation (deg)	1.107	1	1.107	0.082	0.779
Average Eye Angular Velocity (deg/s)	0.746	1	0.746	0.017	0.898
Head Rotation (deg)	90.371	1	90.371	12.186	0.004**
Average Head Angular Velocity (deg/s)	191.405	1	191.405	7.387	0.019*
Pelvis Rotation (deg)	45.847	1	45.847	12.447	0.004**
Peak Pelvis Angular Velocity (deg/s)	1336.815	1	1336.815	2.908	0.112
Pelvis Angular Velocity at Contact (deg/s)	611.298	1	611.298	0.716	0.413
Load Phase (s)	0.002	1	0.002	0.919	0.355
Land Phase (s)	0.000089	1	0.000089	0.177	0.681
Launch Phase (s)	0.001	1	0.001	1.985	0.182
Total Swing (s)	0.005	1	0.005	1.404	0.257
Load-Release Difference (s)	0.009	1	0.009	7.84	0.015*

Elite vs. Sub-Elite					
Kinematic Variable	*Sum of Squares*	*df*	*Mean Square*	*F*	*p-value*
Eye Rotation (deg)	0.068	1	0.068	0.003	0.96
Average Eye Angular Velocity (deg/s)	1.091	1	1.091	0.012	0.913
Head Rotation (deg)	37.572	1	37.572	0.274	0.61
Average Head Angular Velocity (deg/s)	232.985	1	232.985	0.678	0.426
Pelvis Rotation (deg)	157.106	1	157.106	1.183	0.297
Peak Pelvis Angular Velocity (deg/s)	25204.138	1	25204.138	1.995	0.181
Pelvis Angular Velocity at Contact (deg/s)	2329.387	1	2329.387	0.323	0.579
Load Phase (s)	0.271	1	0.271	8.397	0.012*
Land Phase (s)	3.288	1	3.288	187.927	0.016*
Launch Phase (s)	1.77	1	1.77	104.1	0.873
Total Swing (s)	0.751	1	0.751	11.227	0.005**
Load-Release Difference (s)	0.098	1	0.098	5.276	0.039*

Note. * $p < 0.05$. ** $p < 0.01$

Table 4a

Significance of Regression Analysis for Eye and Head Rotation Predicting Pelvis and Phase Kinematics in Elite

Eye Rotation						
Kinematic Variable	B	SE B	β	F	R^2	p-value
Pelvis Rotation (deg)	0.007	0.003	0.266	6.147	0.071	0.015
Land Phase (s)	<0.001	<0.001	0.219	4.094	0.048	0.046
Launch Phase (s)	<0.001	<0.001	-0.246	5.239	0.061	0.025
Head Rotation						
Kinematic Variable	B	SE B	β	F	R^2	p-value
Peak Pelvis Angular Velocity (deg/s)	-2.379	0.597	-0.405	15.887	0.164	< 0.001
Land Phase (s)	-0.003	0.001	-0.274	8.132	0.075	0.005
Load-Release Difference (s)	0.232	0.091	0.273	6.546	0.075	0.012
Eye and Head Rotation						
Kinematic Variable				F	R^2	p-value
Land Phase (s)				10.896	0.214	<0.001
Launch Phase (s)				6.687	0.143	0.002

Table 4b

Significance of Regression Analysis for Eye and Head Rotation Predicting Pelvis and Phase Kinematics in Sub-Elite

Eye Rotation						
Kinematic Variable	B	SE B	β	F	R^2	p-value
Load Phase (s)	<0.001	<0.001	0.245	4.161	0.06	0.045
Head Rotation						
Kinematic Variable	B	SE B	β	F	R^2	p-value
Pelvis Rotation (deg)	-0.805	0.151	-0.551	28.274	0.303	<0.001
Peak Pelvis Angular Velocity (deg/s)	-4.659	1.779	-0.309	6.856	0.095	0.011
Pelvis Angular Velocity at Contact (deg/s)	-2.261	1.024	-0.264	4.873	0.07	0.031
Load Phase	0.006	0.002	0.306	6.704	0.093	0.012
Land Phase (s)	0.003	0.001	0.334	8.142	0.111	0.006
Swing Duration (s)	0.009	0.003	0.383	11.147	0.146	0.001
Load-Release Difference (s)	-0.322	0.101	-0.369	10.216	0.136	0.002
Eye and Head Rotation						
Kinematic Variable				F	R^2	p-value
Pelvis Rotation (deg)				18.029	0.36	<0.001
Load Phase (s)				5.966	0.157	0.004

APPENDIX C: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
4N-64 Brody Medical Sciences Building� Mail Stop 682
600 Moye Boulevard � Greenville, NC 27834
Office **252-744-2914** � Fax **252-744-2284** �
www.ecu.edu/ORIC/irb

Notification of Continuing Review Approval: Expedited

From:	Biomedical IRB
To:	Christopher Curran
CC:	
	Zachary Domire
Date:	1/9/2019
Re:	CR00007481 UMCIRB 17-002568 Biomechanics of Baseball and Softball Swings in Training Settings

The continuing review of your expedited study was approved. Approval of the study and any consent form(s) is for the period of 1/8/2019 to 1/7/2020. This research study is eligible for review under expedited category #4,6,7. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Document	Description
Swing_Drills_Protocol_Changes - Next Level.docx(0.05)	Study Protocol or Grant Application
SwingMoCap_F2017_Consent-NextLevel.pdf(0.08)	Consent Forms
SwingMoCap_F2017_Flyer 18-35.pdf(0.04)	Recruitment Documents/Scripts

The Chairperson (or designee) does not have a potential for conflict of interest on this study.