The Effect of Stride Length on Ocular Tracking of Pitched Balls

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

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Graduate Program in Vision Science

The Ohio State University

2011

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The purpose of this study was to determine the amount of head movement associated with different batter stride lengths, and to determine if the longer stride leads to poorer pitch tracking. Coaches often disagree whether a stride is necessary when hitting, but if they do think a stride is necessary, almost all agree that the stride should be short. They justify this claim because of the presumed negative effect on gaze error associated with a long stride. We hypothesized that when a subject made a long stride toward the pitcher there would be significantly larger amounts of head rotation and translation. This head movement could carry the eyes away from the ball, initiate a VOR response and cause the eyes to move in the opposite direction, or cause excessive variability and lead to inconsistent oscillations in eye position. All of these would translate into poorer tracking of the ball.

A total of 14 subjects with a minimum of at least one year of high school baseball experience were enrolled in this study. They were tested using a pneumatic pitching machine called the Flamethrower under three conditions. In the control condition they just tracked the ball, in the stride condition they made a linear movement of eight inches toward the pitching machine with their front foot, and in the no stride condition they raised their foot and then replaced it in the same location. Each subject viewed 100 pitches at a speed of approximately 80 miles per hour for each of the three conditions.
The balls were pitched from a distance of 43.57 feet from the plate. Eye movements were recorded with the ISCAN infrared eye tracker. Head rotation and translation was recorded using the 3DM-GX1 Microstrain gyro head tracker and the Flock of Birds head tracker. Using a software program, head and eye recordings were synchronized.

A total of 2300 pitches were analyzed and the mean absolute gaze errors, head movements, and eye movements were calculated. Mean absolute gaze errors were very similar initially for each of the three conditions. After 250 ms (14.37 feet from home plate), the no stride condition exhibited a significantly larger gaze error, but gaze errors and standard deviations were very large in all conditions after 250 ms.

Head rotation measured with the Microstrain tracker was initially (at 150 ms) significantly larger for the stride condition, but after 150 ms there was not a significant difference between the conditions. There was a tendency for larger head translations toward the pitching machine to occur in the stride condition. Combining the correlation analysis with the visual graph inspection, these data suggest that a horizontal rotation in the direction of the ball is accompanied by a concomitant horizontal translation in the direction of the ball. Eye movements were initially larger in the stride condition, but after 150 ms the stride and no stride condition were very similar. Both conditions exhibited larger eye movements than the track only control condition.

Overall, tracking performance was not significantly different for subjects who took a stride when compared to subjects who just tracked the ball or subjects who used the no stride hitting approach. The absolute gaze errors were less than 2.5 degrees for the first 250 ms of the pitch for all conditions. After 250 ms, the gaze errors and standard
deviations become quite large. Both translational and rotational head movements were similar between the three conditions and it can be concluded from this study that taking a stride does not lead to more head movement as was predicted by many coaches. Eye movement was also very similar between the no stride and stride conditions, although the track only condition did exhibit smaller eye movements. This indicates that taking a stride does not lead to increased eye movement which was also predicted by many coaches.

From this study, it is reasonable to conclude that taking a stride does not significantly impact tracking a pitched ball. A stride also does not cause a batter to have excessive head and eye movements. It is quite possible that the stride can serve as an important timing mechanism of the swing. This study does not indicate which approach is better, but it does show that a stride is not detrimental for successful tracking.
Dedication

This thesis is dedicated to my biggest supporter, best friend, and love of my life, Amy.
Acknowledgments

I would like to thank Dr. Nick Fogt for all his help throughout this project. I appreciate all the time he spent with me in designing the experiment, analyzing the data, and writing the thesis. He went above and beyond what is expected of an academic advisor. I am so thankful to have gotten the opportunity to work with him and I am extremely happy that I have gained a very good friend through this process.

I would also like to thank my loving wife Amy for all of her support throughout this process. My parents, Daryl and Kathy Atterholt have also been supportive throughout my life and academic career. Without all of these individuals, I would never have been able to complete this project.
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CHAPTER 1: INTRODUCTION

1.1 The Difficulties of Hitting

Ted Williams is widely considered the greatest hitter, if not the greatest baseball player of all time. When questioned, he stated that hitting a baseball was the single most difficult act in all of sports. In a 2003 USA today article, Williams’ opinion was confirmed when “hitting a baseball” was ranked at the top of the list for hardest things to do in all of sports. It was ranked as more difficult than returning a 130 miles per hour (mph) tennis serve, landing a quadruple axel in figure skating, running a marathon, and riding in the Tour de France among other things. Even though to novice sports fans hitting a baseball seems simple, at a scientific level the task is extremely daunting.

There are a variety of factors that contribute to the difficulty of this task, but one of the most important is linear velocity. Major league pitchers can throw pitches that can reach a velocity of 100 mph. Although this velocity in itself is imposing, it is important to understand the dimensions of a baseball diamond to get a greater appreciation of this velocity. The pitcher’s mound is a rectangular piece of rubber located 60 feet and 6 inches from the back of home plate and at an elevation of 10 inches above home plate. At that distance, if a pitcher throws the ball at 95 mph, then the ball will reach the plate in 434 milliseconds (ms). It takes the average human 194 ms to initiate a
swing, so the batter must decide whether or not to swing at the pitch just as the pitch reaches the halfway point to home plate.5 Not only do the batters need to decide if they will swing or not, but they also need to decide where in the hitting zone to swing to make contact with the pitch. To give perspective on the time, a voluntary human blink lasts approximately 150 ms, so in the time that a person can blink three times, the pitch would already be in the catcher’s mitt.6

The previous discussion of velocity involved linear velocity which remains relatively constant throughout the flight path from the release point to crossing home plate. Angular velocity is another important factor that changes dramatically as the pitch nears home plate. The horizontal angle is defined as the angle between the line of sight pointing at the ball and a line perpendicular to the subject’s body.7 Initially, the pitcher will release the ball approximately five feet in front of the pitcher’s mound after striding which is a horizontal angle of 2 degrees. As the ball crosses home plate the horizontal angle will be 90 degrees. The angular change from the pitcher’s release point to a point eight feet in front of home plate is only 12 degrees.8 If the linear velocity of the 95 mph fastball remains constant, the ball will cover the distance from release (55.5 feet) to eight feet from the plate in 341 ms.8 The corresponding angular velocity would be 35.19 degrees/second.8 The change in angle and angular velocity is much greater as the pitch gets closer to the plate. The change from eight feet to four feet in front of the plate is a change of 13 degrees and it takes the ball approximately 29 ms to travel this distance. This leads to an angular velocity of an astounding 452.96 degrees/second.8 At these velocities, it is impossible for the human eye to track the ball all the way to the plate.
1.2 Eye Movements Involved in Hitting

To accurately track a pitch, one option is that batters must either follow the ball with their eyes only while the head remains still. The other option is for the batter to use a combination of eye-in-head rotation and head rotation to track the ball. The combination of the eye-in-head rotation and head rotation are defined as gaze and gaze error is the difference between gaze position and ball position in space. The four types of eye movements that may be relevant while tracking a pitched ball are smooth pursuit movements, saccadic eye movements, the vestibulo-ocular reflex, and vergence movements.

Smooth pursuits are the most commonly used eye movements to track an object. Bahill used an example of a duck hunter sitting in a boat to simplify all of the eye movements. When the hunter spots a duck flying across the sky he will use smooth pursuits to track its path. Pursuits are driven by an object’s image motion on the retina. The goal of the pursuit movement is to match the velocity of the moving object with the velocity of the eye. The latency, or time that it takes for the brain to initiate a pursuit eye movement is 100 ms. Pursuits are ideal eye movements to track a pitched baseball, however their maximum angular velocity has been reported to be 70 degrees/second or possibly 90 to 100 degrees/second. Even on the higher end, smooth pursuit movements do not come close to matching the 450 degrees/second angular velocity that a pitch exhibits from eight feet and in to the plate.

When smooth pursuit eye movements falter, it is necessary to make a faster eye movement to continue to track the ball. These eye movements are called saccades. In
continuing with the duck hunter example, saccades are the quick eye movements used when the hunter is scanning the sky in search of a duck. These eye movements are jerky in nature and are designed to foveate the object of interest. Bahill indicated two ways in which saccades might be used in viewing a pitched ball. In one case, a large saccade is made early in the pitch trajectory. This saccade moves the eyes to a position close to the plate and theoretically allows the ball to be viewed as it is batted. In the other case, the ball might be tracked continuously with a combination of pursuit and interspersed catch-up saccades. Saccades have been shown to reach a peak velocity of over 500 degrees/second. This angular velocity exceeds the 450 degrees/second needed to track a pitch from eight feet and in to the plate, however saccades are designed to only briefly foveate an object and not continually track it like pursuits. The concept of saccadic omission is what limits the saccades from providing continuous retinal image. Saccadic omission is a mechanism where the brain ignores the blurred retinal image that is formed during the saccade. This occurs because the high velocity eye movement would cause a blurred retinal image to occur. Instead of seeing the blurred image, the brain ignores the image that is formed by visually masking the target with either the preceding or succeeding visual stimulus. This masking can occur for upwards of 50 ms before or after the saccade, which would make it extremely difficult to use saccades to track the pitched baseball.

The third eye movement to be discussed is the rotational vestibuloocular reflex (RVOR). In our duck hunting example the RVOR is used to stabilize the hunter’s eyes as the boat rocks back and forth on the water. Head movement can add angular velocity to
the smooth pursuits to allow a batter to have increased gaze pursuit velocity (gaze=eye + head). This may seem like an ideal solution to increase smooth pursuit velocity, however the VOR initiates eye movements to compensate for the rotation of the head. The VOR initiates an eye movement that is opposite in direction to the head movement in order to create a stable retinal image. The latency of the VOR has been shown to be 15 ms. If a batter were to track a pitch using head movement, he or she would need to suppress the VOR. Otherwise the eyes would move back toward the pitcher instead of staying focused on the approaching pitch. A second type of VOR is the translational VOR. The translational VOR is a reflexive eye movement that is a response to head translation. The resultant eye movement is a rotation directed opposite to the head. The translational VOR might be particularly relevant in this study, assuming the stride produces a translational movement of the head.

The final eye movement is a vergence eye movement. In the duck hunter example, a vergence movement would be made to bring the eyes together if the duck comes very close. However, the vergence system has been shown to be negligible in tracking a baseball. The latency of the vergence movement has been found to be approximately 180 ms for the average human and with extensive training, it has been shown to decrease to 65 ms. This latency makes it disadvantageous to use vergence movements to track a pitch. The vergence would change substantially when the ball got very close to the plate, which is also when batters are no longer able to track the pitch. When the pitch is four feet in front of the plate, the vergence angle would be 5.09 prism diopters assuming a pupillary distance of 62 mm (vergence angle=pupillary distance in
cm/target distance in m). Even though the vergence system has been shown to be negligible, having binocular vision has been shown to be helpful to the precise localization of a pitched baseball.¹⁷

1.3 Previous Baseball Eye Movement Studies

There have been a small number of studies done on the eye movements in baseball over the past 60 years. The most famous study was done by Bahill and LaRitz in 1984.⁷ Bahill and LaRitz used graduate students, college baseball players, and a single professional player to monitor the head and eye movements made while tracking a pitch. They were able to collect complete data for only six pitches and partial data from 15 pitches. Even with the limited sample, they were able to make some significant conclusions. They used a plastic ball suspended on a string that ran between the release point and where the batter was standing (60 feet 6 inches).⁷ Using light emitting diodes (LED’s), infrared emitters, and photodectectors they were able to monitor the exact location of both the eye and head in relation to the position of the ball.

Their subjects were graduate students, members of the Carnegie-Mellon University baseball team, and Brian Harper (a professional with the Pittsburgh Pirates at the time). They found that one non-professional subject was able to track the ball well (less than 2 degrees of error) until the ball reached nine feet in front of the plate and then he fell behind the ball. At two feet in front of the plate, the ball was 34 degrees off of the fovea.⁷ The angular velocity calculated from nine feet to two feet in front of the plate was an amazing 507 degrees/second. The professional player was slightly better at tracking the ball as he was able to track the ball accurately (< 2 degrees of error) until the ball was
At two feet in front of the plate, the pitch was only 16 degrees off the fovea, compared to 34 degrees for the non-professional. Another significant finding from this study was that the professional had a peak pursuit velocity of 120 degrees/second which was significantly higher than had ever been recorded previously. He also exhibited a 30 degree/second head velocity leading to a total gaze velocity (eye + head) of 150 degrees/second. The professional also showed more consistency in using both eye and head movements, whereas the non-professionals varied between large head and large eye movements. Bahill and LaRitz hypothesized that the professional player was much better at suppressing his VOR and he was also much better at making an accurate and fast smooth pursuit movement. However, with all of those things said, the professional batter was still not able to track the ball all of the way to the plate.

The very first study that was done to analyze eye and head movements in baseball players was done by Hubbard and Seng in 1954. In this study 42 college players and 59 professional players were used as subjects. Their head and eye movements were monitored using a video camera that was placed 15 feet from the batter. They also used published photographs to determine if head movement was involved with tracking a pitch. Using the photographs and recorded video, they were able to determine that there was very little head movement used in tracking. Although this study was not extremely quantitative in nature, they were able to determine that batters stopped tracking the ball between 8 and 15 feet from the plate. If a batter did not swing at a pitch, then the batters would use their head to track the ball as it crossed the plate. If the batters did swing at the pitch, it appeared as though they were making pursuit movements rather than saccades.
Hubbard and Seng hypothesized that the pursuit movements stopped around eight feet short of the plate because they were ineffective at these close distances or because the bat was in motion already, and eye movements were no longer necessary to guide the swing.\textsuperscript{18}

Hubbard and Seng also showed that there was a relationship between the stride and the timing of the swing.\textsuperscript{18} In general, they found that the batter started his stride when the pitch was released independent of the velocity of the pitch. The completion of the stride varied depending on the velocity of the pitch. If the pitch exhibited a slower velocity, then the stride finished later to match the ball speed. The stride finished at a uniform number of frames before the hit, giving evidence that the stride is used as a timing mechanism to initiate the swing. The duration and speed of the swing were unaltered even when linear velocity of the pitch declined.

Recent work at the OSU College of Optometry has been done under the direction of Dr. Nick Fogt. Three separate experiments have been performed and have only been published in the forms of a Master’s thesis. All experiments have used a pitching machine equipped to throw tennis balls that are labeled with red or black numbers. The subjects also wear eye and head tracking equipment. The first was done by Zimmerman in 2008, where he investigated the tracking ability of subjects when they could freely move their head or when their head was in a fixed position.\textsuperscript{8} He also investigated the accuracy of color and number naming on the tennis balls. Results of this study show that the gaze error at eight feet short of the plate for the fixed head condition was significantly less than the gaze error for the head free condition.\textsuperscript{8} There was not a significant
difference at four feet short of the plate. This indicates that head movement is possibly detrimental to tracking a pitch from the pitcher all the way in to eight feet from the plate. This study also showed that pursuits were the most predominant eye movement used by the batter. Batters initially showed a small saccade at around 155 ms which did not seem to affect tracking accuracy. The color/number naming of the tennis balls was also shown to not relate to a batter’s tracking ability.

Young went into further depth in the analysis of color/number naming of the balls and its related effects on a subject’s tracking ability. Subjects were tested using the same apparatus as was previously used by Zimmerman, but the pitching machine was 60.75 feet from the batter. Pitches were thrown from the pitching machine at an average velocity of 80 mph. He randomized groups into a color/number naming group or a group that was to just track the ball as best possible. The mean gaze error was measured at eight feet from the plate, and subjects in the color/number naming group were found to be significantly worse at tracking the ball accurately. These data have now been reanalyzed such that the mean gaze errors and mean absolute gaze errors were recalculated. The mean gaze error at 13 feet and 8 feet from the batter was less for the track only group. For the absolute gaze errors, from the pitching machine to about 23 feet from the batter, the track only group showed minor improvements in tracking (less than 0.5 degrees). At 18 and 13 feet from the plate, tracking was similar for color/number naming and track only. At 8 feet from the plate, absolute gaze error was better for the color/number naming group.
Burcham\textsuperscript{20} expounded on the theory of VOR suppression by batters which was initially proposed by Bahill and LaRitz.\textsuperscript{7} Small aperture glasses were used to see how well a batter was able to accurately track a ball when forced alter their head and eye movements. The same pitching machine and recording goggles were used, except for the fact that small apertures were place in the goggles that only subtended 3.3 degrees of visual field.\textsuperscript{20} When subjects wore the aperture goggles, their mean gaze errors were significantly better at 300, 305, and 339 ms after the ball left the pitching machine.\textsuperscript{20} The improvement in gaze tracking with the aperture goggles indicated that subjects were able to cancel their VOR successfully.\textsuperscript{20} The apertures also led to an overall decline in the amplitude of head movements.\textsuperscript{20}

1.4 Current Baseball Vision Training

In 2010, the average major league baseball salary was just over $3.3 million.\textsuperscript{21} With this amount of money at stake, players, coaches, and owners are looking for every advantage possible. Many players have begun working with both optometrists and vision therapy specialists to improve their tracking ability and reaction time.\textsuperscript{22} One of the techniques used by players is called the Conditioned Ocular Enhancement Training System, which is a similar setup to the one we have at OSU, which will be further explained in the Methods section.\textsuperscript{22} It is an air cannon that can propel tennis balls upwards of 130 mph and the batter is instructed to attempt to identify both the color and the number on the ball. Some batters will even perform live batting practice with the tennis balls. They can even add an extra dimension of difficulty by swinging only at the red or black numbered balls. Some players, such as Carlos Beltran of the New York
Mets, have even added clauses in their contract that the team must supply one of these pitching machines.\textsuperscript{22}

Another area of intense research, especially in Japan, is that of both dynamic (DVA) and kinetic visual acuity (KVA). DVA is defined by Kohmura and Yoshigi as the ability to discern a horizontally moving object in front of the eye.\textsuperscript{23} They define KVA as the ability to discern an object as the object moves toward the eye.\textsuperscript{23} They used a computer program called “Speesion” which is designed to improve both DVA and KVA. Subjects trained on the Speesion three times per week for eight weeks. At the end there was no significant difference in DVA and KVA for the experimental (Speesion trained) group when compared to the control group (no extra training) when they used an independent vision tester.\textsuperscript{23} When retested on the Speesion device, batters that trained were significantly better. The authors did conclude that the Speesion program can be valuable for baseball players, even though there was no significant difference when using the independent tester.

\textbf{1.5 To Stride or not to Stride?}

There are many conflicting reports on the nature of the proper stride to be used when hitting a baseball. A stride can be defined as the movement of the lead foot linearly toward the pitcher to initiate a weight transfer to start a swing.\textsuperscript{24} Many hitting coaches in all levels of baseball disagree on the proper length of stride that should be taken, or if a stride should be taken at all. Many major league players have had great success with taking either a large stride, or a small or non-existent stride. Hall-of-famer Dave Winfield is a batter that, as Cal Ripken states in his book, “practically steps on the pitcher” when
he swings. Paul Molitor is another baseball legend who often times did not stride at all and kept his front foot planted in the batter’s box. Jeff Bagwell was a perennial all-star at first base and his batting stance was so wide that he took a stride backwards when he swung.

Coaches that are proponents of having a stride argue that the stride is a crucial element for timing. Hubbard and Seng noted that the timeline of the stride showed that it ended 140 ms before the hit. They also noted that as the velocity of the pitch decreased, the timing of the stride duration increased, so a slower pitch led to an extended (in time) stride. It was also shown that the hit occurred on average at 40 ms after the stride ended, indicating that the stride is an essential element for the proper timing of the swing. Ranganathan and Carlton provide data contradictory to Hubbard and Seng. They found that the initiation of the stride as well as its duration are related to the kinematics of the pitcher. The stride duration was longer when the pitcher used a change-up movement pattern when compared to a fastball movement pattern. The stride also began sooner when the pitcher exhibited a change-up movement pattern. They also argue that the swing speed is adjusted depending on the linear velocity of the pitch. Even though Ranganathan and Carlton have different conclusions from Hubbard and Seng, both papers demonstrate the importance of the stride as a timing mechanism for hitting.

Charley Lau is a professional hitting coach that has personally worked with several major league players including Alex Rodriguez, Tony Gwynn, and Dante Bichette. Lau argues that the stride forces the body and the swing to start in the correct direction. Lau argues that the stride stretches the muscles between the upper and lower
body and the stretch that is created leads to the development of maximum power. Other coaches argue that a stride is not necessary, and rotation around a stationary axis is the key to generating power. Rotational power is generated when the knees, hips, and shoulders all rotate in unison. One instructor argues that a no-stride approach to hitting allows the batter to have a quicker response by getting the hands through the hitting zone. This style of hitting is designed for those who are looking to improve their batting average and overall contact with the ball and not necessarily their power hitting.

Welch et al. performed a detailed study on the biomechanics of hitting a baseball. They used 39 professional baseball players with a minimum of 100 at-bats in the minor leagues and a .250 minimum batting average in the 1993 season. Reflective markers were placed at various positions on their body to monitor movement throughout the swing. Batters then hit a number of balls off a batting tee, and the best line drive hits were used for data analysis. The movement of the reflective markers was captured using high speed video. Among other things, the batter’s stride length and direction were measured. The mean stride length was 85 cm, which they defined as the total distance between the two feet at the end of the stride. This is almost identical to the stride length that subjects used in this study. We defined stride length as the linear distance the front foot moved during the stride and not the total length between the two feet. The angle of the stride was also measured, and the mean angle was 12 degrees in the closed direction. This indicates that as batters stride forward, they also tended to stride inward toward the plate.
Most of the coaches that do advocate for a stride when hitting agree that the stride should be short in length. Most coaches agree that the batter should initially begin with their feet shoulder width apart. The stride is recommended to be a variety of distances, ranging from approximately four inches\textsuperscript{25} to half the width of their initial batting stance.\textsuperscript{26} The length of the stride will also vary with the original width of the batter’s stance. If the batter takes a very wide stance, it is unrealistic for them to have a long stride. If the batter has a very narrow stance, they may have a longer stride. There are several arguments that coaches make against a long stride and one of them involves balance. Lau argues that a long stride will cause the batter to lose his dynamic balance and consequently he will not be able to establish a pivot point for rotation.\textsuperscript{26} The other argument involves head and eye movement. Several coaches argue that a long stride will cause excessive head movement and subsequent eye movement.\textsuperscript{24,26} Coaches believe that the consequence of excessive head movement is a reduced ability to track the pitch with the eyes. It is possible that the large head movements could (1) carry the eyes away from the ball, meaning that as the head goes left the eyes are carried with it, (2) the head movement initiates a VOR, so as the head moves toward the pitching machine the eyes respond by moving toward the ball catcher, or (3) the head movement leads to excessive variability and oscillation of the eyes.

1.6 Purpose

The purpose of this study was to determine the amount of head movement associated with different batter stride lengths, and to determine if the longer stride does indeed lead to poorer pitch tracking. Coaches often disagree whether a stride is necessary
when hitting, but if they do think a stride is necessary, almost all agree that the stride
should be short. They justify this claim because of presumed excessive head and eye
movements with a long stride. There have been no studies to evaluate the head and eye
movements involved in different batting strides that I am aware of. In this study, eye and
head tracking equipment was used to determine magnitude of head movement during
different stride lengths and also the gaze error generated from the different stride lengths.
CHAPTER 2: METHODS

2.1 Subject Enrollment and Eligibility

Males between 18 and 50 years of age were recruited from The Ohio State University. Subjects were required to have previous baseball playing experience at the high school and/or college level. Subjects were recruited via email and through word of mouth. The subjects’ average age was 23.9 years (SD=1.49) and had an average of 4.7 years of baseball experience at either the high school or college level (SD=2.27). Subjects were also required to have an unaided visual acuity, or visual acuity with contact lenses of 20/32 (logMAR=0.20) and global stereopsis to check for binocularity. Subjects answered a brief oral survey regarding their previous baseball playing experience. None of the subjects were familiar with the aims of this study.

Approval for this study was granted by The Ohio State University Biomedical Institutional Review Board. Informed consent was obtained from all subjects and each subject signed a Health Insurance Portability and Accountability Act form prior to participation in this study. Each subject participated in only one study visit that lasted approximately 45 minutes.
2.2 Equipment

A compressed air pitching machine called the Flamethrower (Accelerated Baseball Technologies, Barrington, IL) was used to propel or “throw” tennis balls toward the batter. The Flamethrower sits on a platform mounted to a stepladder at a height of five feet. A five foot piece of PVC pipe supported by a tripod extends from the front of the machine and this is where the tennis balls exit. A laser and a photocell were mounted in the end of the PVC where the ball exits the machine. As the ball passed through the laser beam upon exiting the tube, a corresponding drop in voltage from the photocell (routed through an inverting amplifier) occurred. The change in voltage was detected by a computer equipped with a 10 bit analog to digital converter. The end of the tube was 43.57 feet from the position of the batter. A wooden “ball catcher” was fashioned to catch all of the pitches. The wooden box measures 2.5 feet wide by 5 feet tall and is 2.5 feet deep and has heavy cloth mats to absorb the impact of the ball.

The Flamethrower has been shown to be remarkably accurate. Studies have shown the Flamethrower to be able to consistently place pitches in an area that was 16.5 inches high by 15 inches wide at 60 feet 6 inches away. These dimensions fall well within the normal strike zone which is the width of home plate (17 inches) and extends from the batter’s knees to his armpits, which can vary depending on the height of the batter. For a batter that is six feet tall, the approximate height of the strike zone would be 27 inches.

In a separate study, photocell/laser combinations were used to determine the time that elapsed from when the ball passed out of the pitching machine tube to when the ball
reached a certain location. The linear distances and time elapsed are shown in Table 1.

The linear velocity varies slightly throughout the pitch, but always stays between 75 and 80 mph. The angular velocity increases rapidly as the ball gets closer to the batter.

Table 1: Linear distances, time elapsed, and angular change of the ball in reference to the batter whom is 20.5 inches from the center of the plate.

<table>
<thead>
<tr>
<th>Ball Distance from Pitching Machine (feet)</th>
<th>Time (ms)</th>
<th>Angular Change (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.52</td>
<td>150</td>
<td>1.51</td>
</tr>
<tr>
<td>23.36</td>
<td>200</td>
<td>2.58</td>
</tr>
<tr>
<td>29.20</td>
<td>250</td>
<td>4.53</td>
</tr>
<tr>
<td>35.04</td>
<td>300</td>
<td>9.06</td>
</tr>
<tr>
<td>35.62</td>
<td>305</td>
<td>9.86</td>
</tr>
<tr>
<td>39.60</td>
<td>336</td>
<td>20.97</td>
</tr>
<tr>
<td>43.57</td>
<td>373</td>
<td>87.19</td>
</tr>
</tbody>
</table>

2.3 Head and Eye Movement Monitoring

All batters stood in the right handed batter’s box and the eye position was recorded from their lead eye (left eye) which was closer to the pitching machine. Eye movements were monitored using infrared video recording goggles manufactured by ISCAN Incorporated (Burlington, MA). The ISCAN goggles work by tracking the center of the subject’s pupil to detect both horizontal and vertical eye movements, however, only horizontal eye movements were analyzed for this study. The infrared cameras are mounted above the eye to monitor pupil position as the image of the eye is reflected off beam-splitters which are mounted just below the eyes. Estimated spatial resolution of the ISCAN is 15 minutes of arc and the camera speed is 120 Hz. In a separate experiment, the overall accuracy of the ISCAN was determined to be within 0.13 degrees of the
search coil (Appendix A). The output from the ISCAN is recorded in digital format and for analysis it was fed through a digital-to-analog converter (USB 1208FS, Measurement Computing, Norton, MA) for recording. To determine the amplification or gain of the ISCAN, subjects were instructed to fixate a target located 4.89 feet on the wall in front of them, and also a point just below the pitching machine while maintaining a fixed head position (Figure 1). The subsequent angle was 42.99 degrees. The ISCAN digital values for each subject were recorded and an average gain was calculated and used for analysis. Therefore, gain = (ISCAN digital value at tube - digital value at near location) / (42.99 degrees).

Head movement was monitored in two ways and these two devices were pseudosynchronized, meaning they were started at the same time. One tracker that was utilized was the Flock of Birds magnetic tracker (Ascension Technology Corporation, Burlington, VT). The Flock of Birds was used to measure translational head movements. The other head tracker was the 3DM-GX1 (Microstrain, Williston, VA) gyro enhanced head tracker, which was used to measure head rotation. (Appendix B)

2.4 Data Analysis

The analog data were recorded at 2000 Hz from the ISCAN, head tracker, and laser photocell from the end of the tube using Visual Basic 6.0 program (Microsoft Corporation, Redmond, WA). This program was used to synchronize the data from the ISCAN and head tracker with the photocell at the initiation of a pitch. This synchronization allowed the gaze error to be calculated at various intervals throughout the path of the pitch. The gaze error was calculated by subtracting the sum of the
recorded head and eye movements from the change in angular position of the ball at specific times during its flight. An analysis program was used to determine the eye movements, head movements, and gaze error at 150, 200, 250, 300, 305, and 336 ms after initiation of the pitch.

### 2.5 Experimental Design

This study was designed to compare head movements, eye movements, and tracking accuracy (gaze error) for subjects whom were asked to track the ball using three different batting approaches. Each subject was asked to track the ball to the best of their ability under three conditions. These conditions were: (1) while keeping their feet stationary (track only), (2) by making a stride of eight inches in length (stride), and (3) by using the no stride approach. Subjects had an initial stance that forced them to have their feet 26 inches (66 cm) apart. Marks were placed on the floor so the subject was clear where they were to stand for each pitch. In the stride condition, batters were forced to stride eight inches with their front foot (closest to the pitching machine). This gave them a total stride length of 34 inches (86 cm). A paint can was placed at the desired stride length and batters were given several practice trials of the stride condition. They made a stride the desired length and their foot tapped the paint can. In the second condition, batters were instructed to do their normal batting motion except for the actual swing. They were instructed to just lift their foot and then return it to the same position. Finally, subjects were instructed to just track the ball without moving their feet at all. In regards to hand, arm and shoulder movements, batters were given a bat to hold, and were instructed to “Do what you normally do when hitting a ball.” Each batter was randomized
as to which of the three conditions they would perform first. Each batter was given two buckets of tennis balls containing 50 balls each for all three conditions giving a total of 300 pitches. From evidence found in the literature, it was hypothesized that there would be a significantly larger gaze error when subjects were required to make a large stride. This large gaze error would likely result from the large forward head movements pulling the eyes forward, the VOR response to the head movement, or possibly excessive ocular oscillations in eye position as a result of head movement.

In each condition the batter stood in the batter’s box at a distance of 20.5 inches from the center of home plate (Figure 1). The Flame Thrower was 43.57 feet away from the center of home plate (Figure 1). Each pitch varied between five and seven seconds apart. Each condition took approximately 15 minutes for a grand total of 45 minutes for each subject. The study took place in Dr. Nick Fogt’s Sports Vision Research Lab in the basement of Fry Hall at The Ohio State University College of Optometry.
Figure 1. Experimental setup used to calibrate the gain of the ISCAN. The change in digital output was analyzed between the different angles of eye fixation. The first point was at the pitching machine and the second point was an “X” marked on the adjacent wall.
CHAPTER 3: RESULTS

3.1 Data Analysis

The data from the ISCAN eye tracker and Microstrain head tracker were separated into individual traces that corresponded with each pitch. Figure 2 displays an example trace that shows the eye movement, head movement, gaze (eye+head), and ball position. Graphs were then visually inspected for each pitch, and those data from any pitches where there was excessive noise or blinks that occurred less than 400ms after the pitch was released were deleted. Any noise after 400ms was inconsequential as the pitch had already crossed the plate. At this point those data from two subjects were discarded entirely because of a malfunction of the eye tracker, and one subject was lost due to computer malfunction. A number of pitches were also discarded due to slippage of the eye tracker goggle and the presence of blinks.

In total, 2300 pitches remained for analysis after the visual inspection. There were 696 pitches analyzed in the no stride condition, 748 in the stride condition, and 856 in the track only condition. The data from the eye and the rotational head data from the gyro were separated into individual traces that coincided with each pitch.
Figure 2. An example of the trace generated by subject 2. The head movement, eye movement, gaze (eye+head) and ball position are shown. This trace is the typical response seen by the majority of subjects tested. Eye, head, and gaze traces are not corrected for temporal delays in this figure, but were corrected for in the data analysis.

Those raw data from the eye and head movement tracking devices were then run through a custom computer program that performed the following functions. Those data from the eye and head were calibrated. For the head, the calibration factor was determined by comparisons between the tracking device and the Flock of Birds head tracker. For the eye, the calibration factor was the average calibration factor from all 14 subjects utilized in this experiment. Those data from the eye and the head were smoothed using a 40 point averaging filter, and these data were also corrected for a temporal delay.
Next, the computer program calculated the angular change in eye position and the angular change in head position from the beginning of the pitch to 6 elapsed times after the pitch was released. These times were 150, 200, 250, 300, 305, and 336 ms. The ball traveled 17.52, 23.36, 29.20, 35.04, 35.62, and 39.60 feet from the tube respectively at each of these elapsed times (Table 1).

The angular change in eye position was corrected for a small translational artifact that occurs because the eye does not lie at the center of rotation of the head. Thus, the eye is translated in the direction of head rotation. Finally, the angular change in eye rotation and head rotation were added together to attain the angular change in gaze position. Finally, the angular change in gaze position was compared to the angular change in ball position at each of the elapsed times of interest. The mean gaze errors at each of the elapsed times are shown in Table 2. Also shown in Tables 3 and 4 are the changes in head and eye position for each condition at each of the elapsed times. The mean absolute gaze errors are shown in Table 5. The mean gaze error (Table 2) can be used to gather information about subject strategy (eg. gaze lagging behind or leading ahead of the ball). However, the absolute gaze error is the metric used throughout the remainder of this paper to assess the overall accuracy of tracking. We were not concerned with a lead or a lag, but were most concerned with how close they were to the ball. Previous studies have also shown large standard deviations in the mean gaze errors.
Table 2. Mean gaze errors (in degrees) and standard deviations (in degrees) for the three conditions at the given time after the ball was released from the pitching machine. A negative value indicates a lag behind the ball.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>No stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Track Only (deg)</th>
<th>Std Dev (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-0.187</td>
<td>0.96</td>
<td>-0.186</td>
<td>1.02</td>
<td>0.029</td>
<td>0.98</td>
</tr>
<tr>
<td>200</td>
<td>0.232</td>
<td>1.64</td>
<td>0.062</td>
<td>1.46</td>
<td>0.571</td>
<td>1.59</td>
</tr>
<tr>
<td>250</td>
<td>1.208</td>
<td>3.52</td>
<td>0.481</td>
<td>2.71</td>
<td>1.591</td>
<td>2.81</td>
</tr>
<tr>
<td>300</td>
<td>5.193</td>
<td>9.43</td>
<td>3.323</td>
<td>8.01</td>
<td>4.593</td>
<td>7.60</td>
</tr>
<tr>
<td>305</td>
<td>5.757</td>
<td>10.19</td>
<td>3.795</td>
<td>8.73</td>
<td>5.060</td>
<td>8.27</td>
</tr>
<tr>
<td>336</td>
<td>3.935</td>
<td>14.72</td>
<td>1.477</td>
<td>13.19</td>
<td>2.832</td>
<td>12.50</td>
</tr>
</tbody>
</table>

Table 3. Mean rotational head movements (in degrees) and standard deviations (in degrees) for the three conditions at the given time after the ball was released from the pitching machine. Positive values indicate a rightward head movement.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>No stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Track Only (deg)</th>
<th>Std Dev (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2.108</td>
<td>2.12</td>
<td>2.329</td>
<td>2.15</td>
<td>2.058</td>
<td>2.02</td>
</tr>
<tr>
<td>200</td>
<td>3.762</td>
<td>3.24</td>
<td>3.865</td>
<td>3.09</td>
<td>3.613</td>
<td>3.26</td>
</tr>
<tr>
<td>250</td>
<td>6.343</td>
<td>4.89</td>
<td>6.144</td>
<td>4.37</td>
<td>6.116</td>
<td>5.08</td>
</tr>
<tr>
<td>300</td>
<td>10.098</td>
<td>7.29</td>
<td>9.416</td>
<td>6.39</td>
<td>9.809</td>
<td>7.68</td>
</tr>
<tr>
<td>305</td>
<td>10.539</td>
<td>7.59</td>
<td>9.803</td>
<td>6.66</td>
<td>10.240</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Table 4. Mean eye movements (in degrees) and standard deviations (in degrees) for the three conditions at the given time after the ball was released from the pitching machine. A negative value indicates a leftward eye movement.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>No stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Track Only (deg)</th>
<th>Std Dev (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-0.785</td>
<td>1.72</td>
<td>-1.005</td>
<td>1.88</td>
<td>-0.519</td>
<td>1.36</td>
</tr>
<tr>
<td>200</td>
<td>-0.949</td>
<td>2.55</td>
<td>-1.223</td>
<td>2.63</td>
<td>-0.461</td>
<td>2.16</td>
</tr>
<tr>
<td>250</td>
<td>-0.605</td>
<td>3.94</td>
<td>-1.133</td>
<td>3.75</td>
<td>0.004</td>
<td>3.53</td>
</tr>
<tr>
<td>300</td>
<td>4.155</td>
<td>7.74</td>
<td>2.967</td>
<td>7.05</td>
<td>3.844</td>
<td>6.43</td>
</tr>
<tr>
<td>305</td>
<td>5.078</td>
<td>8.19</td>
<td>3.852</td>
<td>7.49</td>
<td>4.679</td>
<td>6.82</td>
</tr>
<tr>
<td>336</td>
<td>11.381</td>
<td>10.32</td>
<td>10.085</td>
<td>9.83</td>
<td>10.641</td>
<td>8.82</td>
</tr>
</tbody>
</table>
Table 5. Mean absolute gaze errors (in degrees) and standard deviations (in degrees) for the three conditions at the given time after the ball was released from the pitching machine.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>No stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Stride (deg)</th>
<th>Std Dev (deg)</th>
<th>Track Only (deg)</th>
<th>Std Dev (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.751</td>
<td>0.62</td>
<td>0.801</td>
<td>0.65</td>
<td>0.732</td>
<td>0.65</td>
</tr>
<tr>
<td>200</td>
<td>1.236</td>
<td>1.10</td>
<td>1.145</td>
<td>0.91</td>
<td>1.181</td>
<td>1.21</td>
</tr>
<tr>
<td>250</td>
<td>2.469</td>
<td>2.78</td>
<td>1.977</td>
<td>1.91</td>
<td>2.220</td>
<td>2.34</td>
</tr>
<tr>
<td>300</td>
<td>7.835</td>
<td>7.38</td>
<td>6.258</td>
<td>5.99</td>
<td>6.352</td>
<td>6.20</td>
</tr>
<tr>
<td>305</td>
<td>8.692</td>
<td>7.84</td>
<td>7.032</td>
<td>6.41</td>
<td>7.090</td>
<td>6.62</td>
</tr>
</tbody>
</table>

Measurements of horizontal head translation and horizontal head rotation were made with the Flock of Birds system, because the Microstrain head tracker is unable to monitor translation. Data were recorded at about 56 Hz and were analyzed off-line using a computer program written specifically for the experiment. A 40 point averaging filter was applied to both the horizontal head translation and the horizontal head rotation prior to any further data analyses. The program was written to detect the beginning of the head movement for each pitch using a velocity criterion. Once the beginning of a head movement was found, then the amplitude of head translation and head rotation were determined at six time intervals after the head movement began. The translation values at these six time intervals were corrected for a measurement artifact that results from the fact that the Flock of Birds receiver was mounted on the ISCAN goggle (Figure 3). This artifact was assessed by placing the ISCAN goggle (with the Flock of Birds receiver mounted on it) on an artificial head (Figure 3). The artificial head had a circumference of 20.75 inches. The head was rotated about a vertical rod. The vertical rod was about 4 inches from the Flock of Birds receiver. The artificial head was rotated through various
horizontal angles. The amplitudes of horizontal rotation and horizontal translation at each angle of rotation were measured. Finally, a linear function relating the horizontal rotation to the horizontal translation was calculated. This linear function was then used to correct the translational values measured on our 12 subjects. The accuracy of the ISCAN was also assessed (Appendix A). The accuracy of the ISCAN was -0.13 degrees ±1.35 degrees.

Figure 3. ISCAN goggle mounted on a model head. The infrared cameras are oriented vertically aimed down toward the clear lenses (beam splitters). The Flock of Birds receiver is the square grey box mounted directly between the two infrared cameras.
3.2 Analysis of Mean Absolute Gaze Errors

The mean absolute gaze errors for each of the three conditions were analyzed at each time of interest using an analysis of variance (ANOVA) (Appendix C, Tables 8-10). Tukey’s multiple comparison test was also performed. The results of these tests indicate that at 150 ms there is not a significant difference between each of the three conditions (P=0.09). Similar results were found at 200 ms, as the data were not significantly different among conditions (P=0.27). At 250 ms there was a significant difference among the groups (P<0.0005). The gaze error for the track only condition and the stride condition was significantly lower than the gaze error for the no stride condition. The stride and track only conditions were not significantly different from one another. The same result was found at 300 ms, 305 ms, and 336 ms as the no stride condition had a significantly higher gaze error than the stride and track only conditions (P<0.0005). Again, the stride and track only groups were not significantly different from one another. After 250 ms, the standard deviations for each of the three conditions became large, so data were less reliable, and drawing clear conclusions was difficult. Standard deviations were much lower under 250 ms, which indicates that the subjects were more consistent earlier in the pitch sequence. At 250 ms, a comparison of the means was done for each subject at the given conditions (Appendix C, Table 8).

3.3 Analysis of Head Movements

A one-way ANOVA using Tukey’s multiple comparison test was used to compare the amounts of head rotation from the Microstrain head tracker at each of the six time intervals for the three conditions (Table 3). At 150 ms, the stride condition had a
significantly larger amount of head rotation compared to both the no stride and track only conditions (P=0.025). However, this difference was only 0.27 degrees or about 15 minutes of arc. There was not a significant difference in head rotation between the three conditions at 200 ms (P=0.28), 250 ms (P=0.62), 300 ms (P=0.19), 305 ms (P=0.17), and 336 ms (P=0.06). Overall, these data suggest that head rotation was similar between the three conditions even though the result was statistically significant at 150 ms.

A one-way ANOVA using Tukey’s multiple comparison test was also used to compare the horizontal translational movements (measured with the Flock of Birds) between the three conditions (Table 6). All of these means are less than one inch.

Table 6. Mean horizontal head translation between the three conditions. Negative values indicate a movement in the direction toward the pitching machine and positive values indicate a movement in the other direction.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean translational head movement (inches)</th>
<th>Standard Deviation (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Stride</td>
<td>-0.141</td>
<td>2.02</td>
</tr>
<tr>
<td>Stride</td>
<td>0.555</td>
<td>0.92</td>
</tr>
<tr>
<td>Track Only</td>
<td>0.757</td>
<td>1.36</td>
</tr>
</tbody>
</table>

The relationship between head rotation and translation was analyzed using a correlation analysis. There was a strong positive correlation between head translation and rotation for the no stride condition (r=0.54, P=0.002, Figure 4). This indicates that head translation helps to explain nearly 29% of the variance in head rotation (r²=0.285). There was also a strong positive correlation between head translation and rotation for the track only condition (r=0.48, P=0.03, Figure 5). This indicates that head translation helps to
explain just over 23% of the variance in head rotation ($r^2=0.232$). There was a weak positive correlation between head translation and rotation for the stride condition ($r=0.20$, $P<0.0005$, Figure 6). This indicates that translation can only explain 4% of the variance in head rotation ($r^2=0.04$). Figure 7 shows all conditions superimposed on one graph.

Figure 4. Scatterplot of head translation versus rotation for the no stride condition.
Figure 5. Scatterplot of head translation versus head rotation for the track only condition.

Figure 6. Scatterplot of the head translation versus head rotation for the stride condition.
Figure 7. The scatterplot generated for all three conditions superimposed on one another.

Referring to Figures 4-7, it can be seen that below 20 degrees of head rotation, these data tend to cluster together. There is a tendency for larger head translations toward the pitching machine to occur in the stride condition, which was expected. Combining the correlation analysis with the visual graph inspection, these data suggest that a horizontal rotation in the direction of the ball is accompanied by a concomitant horizontal translation in the direction of the ball. At head rotations greater than 20 degrees, for the
stride condition the forward head translation is offset by the backward translation that accompanies head rotation.

Even if a subject made a translational head movement of upward of five inches, the required gaze angle does not change drastically at the time intervals that were measured. Table 7 shows the comparison between the required gaze angle when the subject is stationary and it is compared with the gaze angle assuming a five inch forward head translation. The difference in gaze angle is less than 0.5 degrees until 300 ms, which indicated that the head translation did not have a significant impact on gaze error results.

Table 7. The differences in required gaze angle assuming a batter made a five inch forward head translation. These values are compared to the values calculated for a stationary batter.

<table>
<thead>
<tr>
<th>Time Elapsed After Ball Released from Tube</th>
<th>Gaze Angle Required if Stationary (deg)</th>
<th>Gaze Angle if 5 Inches of Translation (deg)</th>
<th>Change in Gaze Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>3.75</td>
<td>3.81</td>
<td>0.06</td>
</tr>
<tr>
<td>200</td>
<td>4.83</td>
<td>4.93</td>
<td>0.10</td>
</tr>
<tr>
<td>250</td>
<td>6.77</td>
<td>6.97</td>
<td>0.20</td>
</tr>
<tr>
<td>300</td>
<td>11.31</td>
<td>11.87</td>
<td>0.56</td>
</tr>
<tr>
<td>305</td>
<td>12.11</td>
<td>12.76</td>
<td>0.65</td>
</tr>
<tr>
<td>336</td>
<td>23.21</td>
<td>25.59</td>
<td>2.38</td>
</tr>
</tbody>
</table>

3.4 Analysis of Eye Movements

A one-way ANOVA using Tukey’s multiple comparison test was used to compare the amounts of eye movement at each of the six time intervals for the three conditions (Table 4). At 150 ms, there was a significant difference in the amount of eye movement (P<0.0005). In the stride condition, eye movements were significantly larger in the negative direction (back toward the pitching machine) when compared to the no stride
and track only condition. At 200 ms, there was a significant difference, as no stride and stride conditions had significantly larger amounts of eye movement (P<0.0005) when compared to the track only condition. In the track only condition subjects exhibit a less prominent RVOR when compared to the other two conditions. There was no difference between the no stride and stride condition. At 250 ms, again there was a significant difference (P<0.0005) between conditions as the track only condition had the smallest degree of eye movement, followed by the stride condition, and finally the no stride condition. The difference was significant between each of the three conditions. At 300 and 305 ms, there the eye movements were significantly smaller in the stride condition when compared to the other two conditions (P=0.004 and 0.006). At 336 ms, there is also a significant difference (P=0.03) as the no stride condition shows the largest eye movements. All eye movements after the 250 ms point were in the positive direction, indicating that they were moving toward the ball catcher and away from the pitching machine.

The data indicated that eye movements were larger for both the stride and no stride conditions when compared to the track only condition. Early in the pitch (150 and 200 ms) the variability in the eye movement was less in the track only condition, but this did not result in greater variability in the absolute gaze errors.

### 3.5 Subject 8 Anomaly

Of the 14 subjects, most traces that were obtained were quite similar. An example of one of these traces can be seen in Figure 2. In this example subject 2 shows an initial pursuit movement and then the head begins to move at approximately 150 ms and as the
ball approaches the batter, a saccade is made to get the eyes as close as possible to the ball. As the ball approaches the plate, the extreme change in angular position is evident, and the subject is no longer able to accurately track the ball with combined eye and head movements. This pattern is seen quite consistently throughout the subjects, with the exception of subject 8. Subject 8 exhibited an instantaneous head movement that was different from any other subject in the study (Figure 8). This head movement initiated a VOR response which cause the eyes to move in a negative direction (toward the pitching machine). This action was seen consistently throughout the three conditions for subject 8, so the data were not excluded. Although this behavior is not typical, it was consistent and there were no grounds for its exclusion.
Figure 8. An example of the trace generated by subject 8. The head movement, eye movement, gaze (eye+head) and ball position are shown. This trace is an abnormal response in that the subject began his head movement instantaneously as the pitch exited the pitching machine. Eye, head, and gaze traces are not corrected for temporal delays in this figure, but were corrected in the analysis described in this study.
CHAPTER 4: DISCUSSION

4.1 Gaze Error

Based on the absolute gaze errors (Table 6), these data indicate that at 150 and 200 ms after the ball has left the pitching machine, the batters performed equally well in each of the three conditions. At 250, 300, 305, and 336 ms the batters performed worse at tracking the ball in the no stride condition when compared to both the track only and stride condition. Although the data are significantly different, above 250 ms these data are difficult to interpret due to the large mean errors and large standard deviations present. Initially, batters perform very well at tracking the ball in all conditions and the standard deviations are quite small. These findings are similar to that found in Bahill’s study in that novice batters had more difficulty tracking the pitch as it approached the batter. After 250 ms, which is about 14 feet in front of the plate the absolute gaze errors are very large and the ability of the subjects to track the ball deteriorated. This could indicate that as the angular velocity increases, subjects make an anticipatory eye movement and are actually ahead of the pitch. This might benefit them in that they are close to the ball when it crosses the plate. The angular velocity change over time can be seen in Figure 9.
Figure 9. The change in angular velocity over time. The velocity begins to increase around 250 ms and the largest increase was found just after 300ms. This graph was generated using a two point difference method where the change in angle was divided by change in time. The results were smoothed with a 40 point filter.

These results are not consistent with the theory that strides lead to poor tracking. The data does not indicate that one approach is better than the other, but it can be inferred that the stride condition does not make tracking worse. These results support the idea that the stride is a good timing device for batters. Previous work by Hubbard and Seng and Ragnathan and Carlton support the fact that the stride provides a crucial element for proper swing timing. It is possible that the stride provides an internal clock that gives the batter a mechanism to maintain proper swing timing and rhythm.
The stride length that was used in this study matched very closely to the measured stride that the average professional hitter used. The no stride condition may have led to poorer tracking because it did not have a spatial component to it. It is possible that the stride gives the batter both a spatial and temporal feedback mechanism. Each batter, through repetition and muscle memory may feel that the forward movement of the stride leads to better timing and the proper initiation of the arm, shoulder, and hip movements necessary for the swing. By just picking up the front foot and replacing it in the same position, there would not be any spatial feedback, and the temporal feedback might have also been disrupted. By forcing the batter to engage in an unfamiliar batting style, it may have disrupted their timing mechanism. They also might have had to consciously think about picking their foot up and putting it right back down. Batters normal stride length was not measured prior to this study, but if previous studies are any indication, most batters do engage in some sort of stride.

The no stride condition might have been a distraction to the batter. Previous work by Castaneda and Gray has shown that when experienced batters must attend to an internal stimulus, batting performance suffers. They used both experienced and novice baseball players and required them to attend to an internal stimulus (hand motion when swinging) and external stimulus (bat motion). They found that when experienced players focused on their hand movement when swinging, their batting performance deteriorated. There was not a significant difference in the novice batters. This supports the idea that by forcing the experienced batters in this study to lift their foot and replace it in the same position, the attention involved in that task can lead to poorer tracking performance.
4.2 Head Movements

Initially the batters exhibited a significantly larger head rotation in the stride condition. This was only evident at the 150 ms recording. At each subsequent recording there was not a significant difference between the three conditions. Even though the difference was significant, the mean head rotation was only 0.2 degrees more than that found in the no stride condition. Even though the data were not statistically significant, forward translations were more common in the stride condition. These data do marginally support the theory that many coaches share in that a large stride leads to a larger head movement.\textsuperscript{24,27}

Using a correlation analysis, it was determined that there was a strong positive correlation between head rotation and translation in the no stride and track only conditions. Therefore, head rotations in the direction of the ball are often accompanied by head translations in the direction of the ball.

In summary, the stride seems to increase the likelihood of a larger forward translation, however this translation only has a small effect on the gaze angle required to fixate the ball (Table 7), and has no effect on the absolute gaze error. There does seem to be a larger amount of variability in the stride condition compared to the no stride and track only conditions. The overall mean values do not indicate more movement in the stride condition, but the graphs indicate that there is a greater chance of having a large translational head movement when a stride is performed.
4.3 Eye Movements

Eye movements were significantly smaller in the track only condition when compared to the no stride and stride conditions. After 250 ms, the standard deviations become quite large and make the data difficult to interpret. These data suggest that the RVOR played less of a role in the track only condition. Again the data must be qualified because the eye movements within one degree of one another for the first 250 ms. Given that the variability of eye movement was slightly lower for the track only condition, it does appear that lifting the lead foot correlates with greater eye movement variability. However, this variability does not impact the mean absolute gaze error or the variability of the gaze error.

4.4 Subject 8 Anomaly

In the previous four studies done in Dr. Fogt’s baseball tracking lab, the behavior exhibited by subject 8 has not been seen. This subject began moving his head almost instantly as the ball left the pitching machine. This early head movement also caused an eye movement in the opposite direction from the RVOR. These data were not excluded from analysis because the response was so consistent. Throughout all three conditions, subject 8 consistently showed this same behavior. From this consistency it was determined that an error did not occur in recording and the subject actually was moving his head right as the pitch was released. Since there was no justification for exclusion, all the data for subject 8 were included in the analysis of gaze error, head movement, and eye movement. This behavior is perplexing and the only explanation that I can offer is that subject 8 is a left-handed batter. Due to the recording program, batters were forced to
bat from the right hand batter’s box. If the batter is accustomed to batting left-handed, then he might rely heavily on his right eye, which is closest to the pitcher. When forced to use his non-dominant left eye by batting right-handed, he may have compensated by moving his head a large amount and very early in the pitch. This particular subject was not an inexperienced baseball player as he had played all four years in high school and two years at the collegiate level. If the subject had little baseball experience then I would predict inexperience as the cause of the unusual head movements.

4.5 Conclusions

Tracking performance was not worse when subjects took a stride when compared to when they just tracked the ball or used the no stride hitting approach. By analyzing the translational head movements, there seems to be more variability and a higher likelihood for larger head movements when a stride is made. The increased variability and size of head movements did not adversely affect the tracking ability (absolute gaze error) for the stride condition. Eye movement was also very similar between the no stride and stride conditions. The track only condition did exhibit smaller eye movements most likely due to better suppression of the VOR. Even though the eye movements were larger for the stride and no stride condition, again gaze error did not seem to be adversely affected.

From this study, it is reasonable to conclude that taking a stride does cause a significant difference in tracking a pitched ball. A stride can minimally increase head and eye movements, but this increase does not adversely affect gaze error. The aim of this was not to determine which hitting approach was better suited for all batters, but it was aimed at determining the affect that a stride had on gaze error, head movement, and eye
movement. It is quite possible that the stride can serve as an important timing mechanism of the swing. Likely if a batter is successful at hitting by using a stride, then I do not have sufficient evidence to say what he is doing is incorrect. Likewise, if a batter is successful using the no stride approach then I would not recommend a change in style. This study does not indicate which approach is better, but it does show that a stride is not detrimental for successful tracking.

Future work could be done to analyze different types of pitches. It would be interesting to see if a similar performance was exhibited with a curve ball or a knuckle ball when compared to a fastball. Another possibility is that subjects could be allowed to swing at the pitch. If subjects were allowed to swing, it would be interesting to see if they exhibited a similar behavior. Another option would be to use a live pitcher instead of a pitching machine. This would be useful to test the stride timing and the pitching motion.
REFERENCES


19 Young, J. Tracking a Baseball During a Color Naming Task. MS Thesis. The Ohio State University. 2009.


22 Dodd, M., When it Comes to Hitting a Baseball, the Eyes Have it. *USA Today*. June 2, 2005.


APPENDIX A: ISCAN CALIBRATION

The accuracy of the ISCAN eye tracker was assessed in the following way. The subject wore both a search coil (the gold standard eye tracker) on the left (lead) eye and the ISCAN video eye-tracker. The subject stood within a magnetic field coil cage (Remmel Labs) placed 39 feet 7 inches from the pitching machine used throughout the experiment. The subject then attempted to partially or fully track pitches thrown by the pitching machine with the eyes while the head was kept as still as possible. Analog signals from both the search coil and the ISCAN video-tracker (left eye) were recorded simultaneously at 2000Hz for 14 pitches. The eye movement recordings for both eyetracking methods were calibrated based on a two-point calibration performed at the beginning of the experiment. Those data from the ISCAN were smoothed using a 40 point averaging filter (no filtering was applied to the search coil data). The eye movement amplitudes (as determined from the search coil) ranged from 21.6 deg to 47.2 deg (mean = 33.4deg ± 7.7deg). The eye movement typically consisted of a rapid movement followed by a slower drifting movement.

Those data from the two devices were parsed up into 14 separate data sets. Each data set included the tracking eye movement, along with some or all of the eye movement as gaze was returned to the pitching machine in anticipation of the next pitch. Finally,
some of the data sets contained a small number of data points prior to and after the eye movements. The eye movement traces from the two devices were similar, but it was clear that the ISCAN had a discernible delay compared to the search coil. This delay was similar from pitch to pitch. The ISCAN data were “corrected” for this delay, and then the angular values from the eye trackers were each adjusted if necessary such that the beginning of each data set was zero degrees. After that the difference in ISCAN and coil positions was determined for all pitches. Differences were determined every 0.0005s. This resulted in 18,800 comparisons. The mean difference in position between the two eye trackers was –0.13 deg (the minus sign indicates that the ISCAN lagged behind the search coil). The standard deviation of this mean was 1.35 deg.
APPENDIX B: HEAD TRACKER CALIBRATION

The Flock of Birds consists of a receiver, which is mounted to the ISCAN goggle, and a transmitter which emits a magnetic field. As the receiver moves through the magnetic field generated by the transmitter, positional data is generated and recorded. The spatial resolution of the Flock of Birds is 0.5 degrees and temporal resolution was 144 Hz. Head movements were also recorded using the 3DM-GX1 (Microstrain, Williston, VA) gyro enhanced head tracker. This head tracker was mounted to the top of a batting helmet that each subject wore, and it combines three accelerometers, three angular rate gyros, and three magnetometers to measure the head movements in three axes. Only horizontal head movements were measured in this study. The accuracy of the 3DM-GX1 gyro was assessed in a separate experiment.

The accuracy of the Microstrain head tracker in this task was assessed in the following way. An individual wore a calibrated search coil attached to the top of a batting helmet. The batting helmet was the same as that used in the main experiment, and therefore the Microstrain device was attached to the top of the helmet. The subject attempted to track 25 pitches from the pitching machine with the head. Different amplitudes of head rotation were made in response to the pitches. Synchronized analog recordings were made from both the Microstrain head tracker and the search coil at 2000 Hz. Once these data were gathered they were calibrated and then the Microstrain data
were smoothed using a 40 point averaging filter. A total of 17 pitches were used for analysis. Those data for each pitch were analyzed independently. The range of head movements (based on the search coil recordings) was 14.10 degrees to 117.04 degrees and the mean head rotation was 48.40 degrees ± 32.20 degrees. After that, the beginning of the traces was corrected to zero degrees. Those data from the two trackers for each pitch were then plotted against one another and a discernible temporal delay was noted in the Microstrain head tracker. Then, the difference in angle between the two trackers was calculated every 0.0005 seconds. The mean differences between the two trackers at head rotations up to 50 degrees are shown in Table 11. At head rotation angles greater than 50 degrees, the two trackers could give very different values, so data for head rotation angles above 50 degrees are not included in this table. Positive head rotations indicate a Microstrain value greater than the search coil value.

Table 11. The mean differences between the Microstrain head tracker and the Flock of Birds head tracker at given head rotation ranges.

<table>
<thead>
<tr>
<th>Number of Points</th>
<th>Head Rotation Range (degrees)</th>
<th>Mean Differences Between the Head Trackers (degrees)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7048</td>
<td>≤10</td>
<td>0.51</td>
<td>0.59</td>
</tr>
<tr>
<td>3155</td>
<td>&gt;10 - ≤20</td>
<td>1.36</td>
<td>1.00</td>
</tr>
<tr>
<td>1343</td>
<td>&gt;20 - ≤30</td>
<td>1.77</td>
<td>0.94</td>
</tr>
<tr>
<td>1027</td>
<td>&gt;30 - ≤40</td>
<td>1.19</td>
<td>1.13</td>
</tr>
<tr>
<td>1176</td>
<td>&gt;40</td>
<td>0.66</td>
<td>1.16</td>
</tr>
</tbody>
</table>
APPENDIX C: INDIVIDUAL MEAN GAZE ERRORS

Table 8. Mean absolute gaze errors and standard deviations for individual subjects at the six time intervals after the ball left the pitching machine for the no stride condition. A comparison between conditions was added for the 250 ms recording (TO=track only).

<table>
<thead>
<tr>
<th>Subj. #</th>
<th>Years of Baseball Experience</th>
<th>Gaze Error at 150 ms (deg)</th>
<th>Gaze Error at 200 ms (deg)</th>
<th>Gaze Error at 250 ms (deg)</th>
<th>Vs. other conditions</th>
<th>Gaze Error at 300 ms (deg)</th>
<th>Gaze Error at 305 ms (deg)</th>
<th>Gaze Error at 336 ms (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>1.80 (±0.52)</td>
<td>2.74 (±0.72)</td>
<td>3.65 (±1.52)</td>
<td>&lt;stride &gt;TO</td>
<td>7.19 (±2.26)</td>
<td>7.89 (±2.36)</td>
<td>18.59 (±2.66)</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.68 (±0.55)</td>
<td>1.40 (±0.94)</td>
<td>3.42 (±2.10)</td>
<td>&gt;stride &gt;TO</td>
<td>11.08 (±8.11)</td>
<td>12.67 (±8.73)</td>
<td>18.74 (±9.86)</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.46 (±0.39)</td>
<td>0.59 (±0.44)</td>
<td>0.97 (±1.16)</td>
<td>&lt;stride &lt;TO</td>
<td>4.66 (±4.90)</td>
<td>5.21 (±4.98)</td>
<td>7.95 (±4.82)</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.49 (±0.46)</td>
<td>1.40 (±0.96)</td>
<td>3.37 (±1.62)</td>
<td>&gt;stride &gt;TO</td>
<td>5.98 (±4.46)</td>
<td>6.52 (±4.97)</td>
<td>9.16 (±7.15)</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>0.68 (±0.40)</td>
<td>0.91 (±0.50)</td>
<td>1.55 (±0.91)</td>
<td>&lt;stride &lt;TO</td>
<td>3.55 (±1.78)</td>
<td>3.88 (±1.97)</td>
<td>10.50 (±4.21)</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>0.58 (±0.48)</td>
<td>1.16 (±1.01)</td>
<td>1.88 (±1.59)</td>
<td>&lt;stride &lt;TO</td>
<td>2.97 (±3.01)</td>
<td>3.28 (±3.20)</td>
<td>5.50 (±3.89)</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>0.44 (±0.28)</td>
<td>0.43 (±0.31)</td>
<td>1.05 (±1.52)</td>
<td>&gt;stride &gt;TO</td>
<td>10.28 (±5.00)</td>
<td>11.45 (±4.94)</td>
<td>11.38 (±4.19)</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>0.73 (±0.63)</td>
<td>0.95 (±1.38)</td>
<td>1.91 (±3.08)</td>
<td>&gt;stride &gt;TO</td>
<td>7.38 (±6.03)</td>
<td>8.15 (±6.15)</td>
<td>7.96 (±5.91)</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>0.93 (±0.66)</td>
<td>1.79 (±0.99)</td>
<td>4.35 (±3.06)</td>
<td>&gt;stride &gt;TO</td>
<td>17.41 (±8.88)</td>
<td>19.07 (±8.92)</td>
<td>22.60 (±7.63)</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>0.70 (±0.44)</td>
<td>2.03 (±2.75)</td>
<td>8.27 (±10.1)</td>
<td>&gt;stride &gt;TO</td>
<td>18.68 (±15.40)</td>
<td>20.07 (±15.5)</td>
<td>24.52 (±14.5)</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>0.78 (±0.61)</td>
<td>0.90 (±0.72)</td>
<td>1.51 (±2.21)</td>
<td>&lt;stride &lt;TO</td>
<td>4.43 (±5.46)</td>
<td>4.91 (±5.72)</td>
<td>8.67 (±4.13)</td>
</tr>
</tbody>
</table>
Table 9. Mean absolute gaze errors and standard deviations for individual subjects at the six time intervals after the ball left the pitching machine for the stride condition.

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Years of Baseball Experience</th>
<th>Gaze Error at 150 ms (deg)</th>
<th>Gaze Error at 200 ms (deg)</th>
<th>Gaze Error at 250 ms (deg)</th>
<th>Gaze Error at 300 ms (deg)</th>
<th>Gaze Error at 305 ms (deg)</th>
<th>Gaze Error at 336 ms (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (±Std Dev)</td>
<td>4</td>
<td>1.67 (±0.60)</td>
<td>2.55 (±0.88)</td>
<td>3.87 (±1.48)</td>
<td>7.76 (±2.05)</td>
<td>8.48 (±2.14)</td>
<td>18.89 (±3.35)</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.65 (±0.53)</td>
<td>0.79 (±0.64)</td>
<td>1.04 (±0.80)</td>
<td>4.16 (±4.07)</td>
<td>4.85 (±4.31)</td>
<td>8.57 (±5.54)</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.58 (±0.52)</td>
<td>1.02 (±0.73)</td>
<td>1.53 (±1.37)</td>
<td>4.26 (±6.04)</td>
<td>4.96 (±6.50)</td>
<td>9.03 (±5.88)</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.50 (±0.46)</td>
<td>1.23 (±0.92)</td>
<td>3.01 (±1.47)</td>
<td>5.98 (±4.31)</td>
<td>6.58 (±5.02)</td>
<td>9.69 (±8.80)</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>0.83 (±0.57)</td>
<td>1.28 (±0.88)</td>
<td>2.34 (±1.44)</td>
<td>4.28 (±2.13)</td>
<td>4.68 (±2.20)</td>
<td>12.69 (±3.54)</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>1.16 (±0.75)</td>
<td>1.44 (±0.39)</td>
<td>2.15 (±1.46)</td>
<td>3.37 (±2.72)</td>
<td>3.61 (±2.98)</td>
<td>7.63 (±4.13)</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>0.35 (±0.26)</td>
<td>0.46 (±0.33)</td>
<td>0.88 (±1.22)</td>
<td>8.38 (±4.28)</td>
<td>9.51 (±4.25)</td>
<td>9.16 (±3.95)</td>
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<td>10</td>
<td>4</td>
<td>0.63 (±0.53)</td>
<td>0.80 (±0.66)</td>
<td>1.77 (±2.57)</td>
<td>7.80 (±6.93)</td>
<td>8.68 (±7.22)</td>
<td>10.63 (±7.08)</td>
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<tr>
<td>12</td>
<td>8</td>
<td>0.92 (±0.57)</td>
<td>1.41 (±0.83)</td>
<td>2.08 (±1.22)</td>
<td>6.79 (±7.03)</td>
<td>7.84 (±7.52)</td>
<td>11.02 (±7.53)</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>0.50 (±0.50)</td>
<td>0.65 (±0.59)</td>
<td>1.70 (±1.98)</td>
<td>13.64 (±8.76)</td>
<td>15.38 (±9.15)</td>
<td>21.61 (±11.09)</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>0.97 (±0.61)</td>
<td>1.09 (±0.74)</td>
<td>2.13 (±2.35)</td>
<td>6.11 (±7.89)</td>
<td>6.81 (±8.34)</td>
<td>11.36 (±9.14)</td>
</tr>
</tbody>
</table>
Table 10. Mean absolute gaze errors and standard deviations for individual subjects at the six time intervals after the ball left the pitching machine for the track only condition.

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Years of Baseball Experience</th>
<th>Gaze Error at 150 ms (deg)</th>
<th>Gaze Error at 200 ms (deg)</th>
<th>Gaze Error at 250 ms (deg)</th>
<th>Gaze Error at 300 ms (deg)</th>
<th>Gaze Error at 305 ms (deg)</th>
<th>Gaze Error at 336 ms (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (±Std Dev)</td>
<td>4</td>
<td>1.13 (±0.34)</td>
<td>1.39 (±0.96)</td>
<td>1.68 (±1.93)</td>
<td>4.08 (±2.23)</td>
<td>4.59 (±2.22)</td>
<td>12.99 (±4.00)</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.62 (±0.61)</td>
<td>1.09 (±0.61)</td>
<td>2.00 (±1.76)</td>
<td>4.46 (±4.16)</td>
<td>5.09 (±4.65)</td>
<td>7.17 (±5.11)</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.47 (±0.41)</td>
<td>0.64 (±0.58)</td>
<td>1.31 (±2.16)</td>
<td>5.11 (±6.12)</td>
<td>5.91 (±6.34)</td>
<td>8.59 (±5.36)</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.52 (±0.38)</td>
<td>0.99 (±0.75)</td>
<td>2.72 (±1.19)</td>
<td>4.57 (±2.86)</td>
<td>4.91 (±3.35)</td>
<td>7.85 (±5.50)</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>0.53 (±0.68)</td>
<td>0.68 (±0.50)</td>
<td>1.49 (±2.01)</td>
<td>3.53 (±3.44)</td>
<td>3.90 (±3.51)</td>
<td>7.34 (±4.62)</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>1.40 (±1.06)</td>
<td>3.01 (±2.04)</td>
<td>5.18 (±2.99)</td>
<td>7.32 (±4.65)</td>
<td>7.50 (±4.90)</td>
<td>5.93 (±5.46)</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>0.26 (±0.22)</td>
<td>0.38 (±0.27)</td>
<td>0.67 (±0.87)</td>
<td>5.36 (±3.76)</td>
<td>6.34 (±3.89)</td>
<td>6.89 (±3.09)</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>0.61 (±0.47)</td>
<td>0.59 (±0.50)</td>
<td>0.85 (±0.79)</td>
<td>3.09 (±2.10)</td>
<td>3.59 (±2.30)</td>
<td>8.37 (±5.06)</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>0.81 (±0.54)</td>
<td>1.70 (±0.89)</td>
<td>3.67 (±1.92)</td>
<td>15.01 (±8.22)</td>
<td>16.76 (±8.41)</td>
<td>21.24 (±8.18)</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>1.11 (±0.88)</td>
<td>1.80 (±1.28)</td>
<td>4.18 (±2.52)</td>
<td>13.94 (±7.93)</td>
<td>15.62 (±8.26)</td>
<td>22.32 (±8.46)</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>0.71 (±0.55)</td>
<td>0.82 (±0.67)</td>
<td>1.56 (±1.95)</td>
<td>6.17 (±6.19)</td>
<td>6.90 (±6.39)</td>
<td>10.81 (±5.25)</td>
</tr>
</tbody>
</table>