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ORIGINAL ARTICLE

A Method to Monitor Eye and Head Tracking Movements in College Baseball Players

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ABSTRACT
Purpose. This study had two purposes. The first was to develop a method to measure horizontal gaze tracking errors (based on synchronized eye and head tracking recordings) as subjects viewed many pitched balls. The second was to assess horizontal eye, head, and gaze tracking strategies of a group of Division 1 college baseball players.
Methods. Subjects viewed, but did not swing a bat at, tennis balls projected by a pneumatic pitching machine. Subjects were to call out numbers and the color of these numbers (black or red) on the balls. The trajectory of each pitch was very predictable. Eye and head movements were monitored with a video eye tracker and an inertial sensor, respectively, and these movements were synchronized with ball position using an analog recording device. Data were analyzed for 15 subjects.
Results. Eye rotation, head rotation, gaze errors (GEs), and unsigned gaze errors (UGEs) were calculated at various elapsed times. On average, subjects tracked the pitched ball with the head throughout the pitch trajectory, while the eye was moved very little until late in the pitch trajectory. On average, gaze position matched the target position throughout the pitch trajectory. There was some variability in the mean amplitudes of head and eye movement between subjects. However, the eye and head were related by a common rule (partial rotational vestibulo-ocular reflex suppression) for all subjects. Although the mean amplitudes of the GE and UGE varied between subjects, these means were not consistent with anticipatory saccades for any subject.
Conclusions. On average, Division 1 college players tracked the pitched ball primarily with the head and maintained gaze close to the ball throughout much of the pitch trajectory. There was variability between subjects regarding the head and eye movement amplitudes and GEs, but, overall, all subjects maintained gaze close to the ball throughout the pitch trajectory despite the fact that these individuals were not batting.
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Key Words: baseball, eye movements, head movements, gaze tracking, sports vision

Hitting a baseball is a remarkably difficult task. Pitches can reach linear velocities of 90 miles per hour or higher. If a pitcher releases the ball 5 ft in front of the pitching rubber, a pitch averaging 90 miles per hour will reach home plate in about 420 milliseconds. In that case, because the swing requires 160 to 200 milliseconds,[1–3] the batter has only about 220 to 260 milliseconds to decide when and where the ball will arrive and whether to swing the bat.

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Many attributes may contribute to successful hitting. These include physical attributes such as strength, swing speed, and hitting biomechanics.[4–6] Furthermore, the use of prepitch information such as a pitcher's tendencies, the pitch count, and the history of previous pitches can help in predicting when and where a pitch will arrive.[4,7]

Ocular attributes may also play a role in hitting. A batter's static visual acuity (SVA) could play a role. Visual cues about pitch trajectory may be available from the launch angle of the pitcher's arm, the position of the pitcher's fingers on the ball, and the rotational characteristics (seam orientation) of pitched balls.[4,8–14] Reasonably good SVA would be needed to pick up these visual cues.

Static visual acuity may also be important in judging time to collision (TTC). Here, TTC refers to the time at which the ball arrives at the plate. Estimates of TTC for an approaching object can be made using changing size and changing disparity information.[4,11,15,16] Presumably, better SVA would result in more accurate TTC estimates.

A second ocular attribute that may play a role in hitting is ocular gaze tracking. Hubbard and Seng[2] used a video camera to monitor the head and eye movements of professional baseball players during batting practice. These investigators found that batters used smooth pursuit eye movements to track the ball. They showed that ocular tracking stopped when the ball was 8 to 15 ft from the plate. They stated that pursuit movements were stopped at near distances either because these movements were too slow to track the ball or because the bat was already in motion and eye movements could no longer guide the swing. Finally, Hubbard and Seng[2] showed that little head movement was used for tracking except when batters chose not to swing.

Bahill and LaRitz[17] performed a study on head and eye tracking movements during a baseball pitch. The ball was pulled toward the "batter" on a string attached to a motor. Vertical ball movement was minimized, and subjects were not permitted to swing. This is, to our knowledge, the only study to accurately quantify head and eye movements during baseball pitches. The subjects included graduate students, students on the Carnegie-Mellon University baseball team, and a Major League Baseball (MLB) player. Horizontal head and eye movement data over the entire pitch trajectory were collected for six pitches. Partial data were collected from another 15 pitches. The pursuit eye movements of the MLB player in the study were faster than those of other subjects. The MLB player had a pursuit eye velocity of 120 degrees per second, much faster than normative pursuit values reported in the literature.[18] The high pursuit eye velocity of the MLB player (combined with head movements) allowed him to track the ball accurately (errors less than 2 degrees) to about 5.5 ft from the plate. The students could track the ball accurately to only about 9 ft from the plate.

Bahill and LaRitz[17] reported that the MLB player used equal-amplitude head and eye movements to track the ball. The less experienced subjects used large head movements (with little eye movement) or large eye movements (with little head movement) to track the ball.

Interestingly, the MLB player demonstrated a small eye movement opposite in direction to both head and ball movement early in the pitch. Bahill and LaRitz[17] attributed this eye movement to the rotational vestibulo-ocular reflex (RVOR). The RVOR is generated in response to head rotation and rotates the eyes opposite to the head to maintain a constant gaze position.[19–21] When the head is rotated in the same direction as a pursuit target, it may be necessary to suppress the RVOR.[22–24]

After the brief period over which the RVOR occurred, the eye movement direction of the MLB player reversed. Bahill and Laritz[17] suggested that some students may have minimized head movements because of ineffective RVOR suppression.

Finally, two distinct tracking strategies were identified by Bahill and LaRitz.[17] One strategy was to maintain fixation on the ball as long as possible (Fig. 1). On the other hand, one subject minimized his head movement during the pitch (Fig. 2). After the first third of the pitch, this subject executed a saccade, placing the eyes ahead of the ball. This anticipatory saccade allowed the batter to briefly foveate the ball shortly before it crossed the plate. Foveating the ball late in the pitch did not appear to be possible if the ball were tracked continuously because of the ball's high angular velocities.

Bahill and LaRitz[17] and Gray[4] both suggest that tracking the ball throughout its trajectory (Fig. 1) is an appropriate strategy for hitting a ball because this maximizes the time over which the ball is fixated. These authors suggest that making an anticipatory saccade to fixate the ball when it reaches the plate (Fig. 2) may help the batter to predict the locations of future pitches. The anticipatory movement strategy may also provide feedback about bat location compared with ball location. If that is the case, then anticipatory saccades may be less likely when pitch speed and trajectory are predictable.

A more specific advantage of continuous tracking of a pitched ball is that this strategy may improve TTC estimates compared with fixation where an object will ultimately arrive.[25] This has been shown under prediction-motion (PM) conditions, in which the subject views the initial portion of the object's trajectory, then the object is occluded and the subject judges when the object will arrive at a particular location. It has been suggested that extraretinal eye position information (EEPI) during pursuit tracking is what aids in estimating TTC.[25]

To bat a pitched ball, a batter must decide "when" the pitch will arrive at the plate (TTC) and "where" the pitch will be located when it arrives at the plate.[4,17,26] Although pitched balls follow a parabolic trajectory, horizontal gaze tracking would be of greatest value (compared with vertical tracking) in estimating TTC. On the other hand, EEPI associated with vertical pursuit tracking may help in predicting the spatial location of the ball.

Gaze tracking behavior in sports is an area of active research. In addition to baseball,[17] anticipatory gaze movements that place the eyes at the interception point with the ball have been reported in cricket,[27–29] table tennis,[30] and squash.[31] The pervasive nature of anticipatory movements has led to the suggestion that continuous gaze tracking of an approaching object is unnecessary for accurate target interception. This contrasts with results under PM conditions.[25] Of course, unlike the experiments in sports, peripheral vision of the approaching object is not allowed under PM conditions.

Although Bahill and LaRitz[17] demonstrated differences in the efficiency of and strategies for horizontal ocular tracking between an experienced baseball player and less experienced players, the small number of pitches from which data were gathered led us to reexamine the issue.

The project had two purposes. The first purpose was to develop a method by which horizontal gaze tracking errors could be measured as subjects viewed pitched balls. We focused on horizontal tracking for two reasons. First, pitches thrown by our pitching machine resulted in much larger changes in horizontal visual angle than vertical visual angle. Second, horizontal tracking is more closely associated with TTC estimates. The second purpose was to assess horizontal head and eye movement strategies used in tracking pitched balls and to determine how consistent these strategies were between similarly accomplished subjects.

METHODS

This study was approved by The Ohio State University Biomedical Institutional Review Board. All subjects signed an

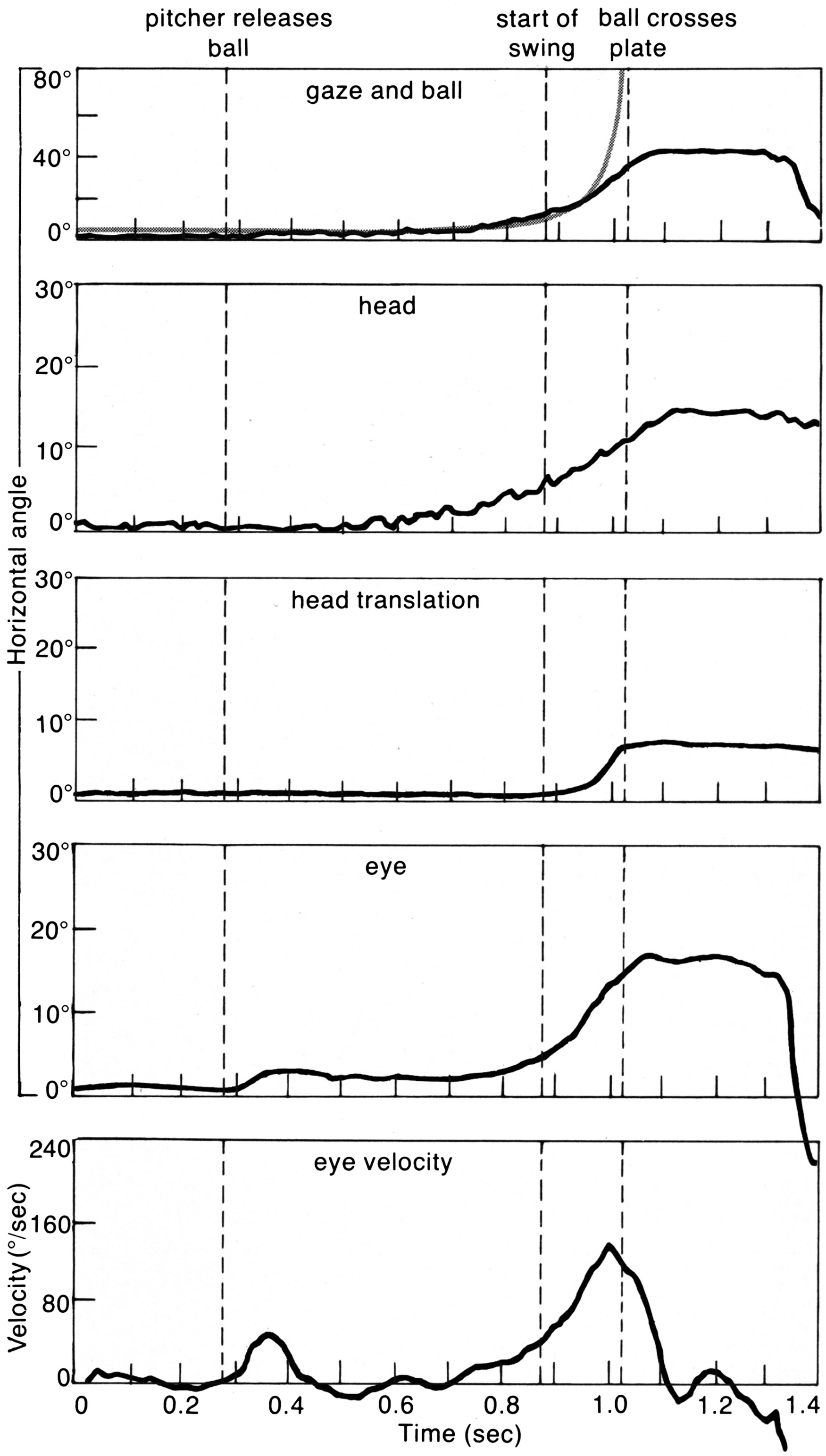

FIGURE 1.

Gaze position, head rotation, head translation, eye rotation, and eye velocity as measured from a Major League Baseball player by Bahill and LaRitz.[17] The subject tracks the ball (60 miles per hour simulated fastball) smoothly throughout much of the pitch trajectory. Reprinted with permission from Bahill and LaRitz. Why can't batters keep their eyes on the ball. Am Sci 1984;72:249-53. ©1984 Sigma Xi, The Scientific Research Society.

informed consent form and a HIPAA form before participation. Data were collected from 18 active members of a Division 1 intercollegiate baseball team. All subjects were less than 30 years of age. Pitchers were excluded. Monocular visual acuity was tested with a Bailey-Lovie chart[32] using the subjects' habitual correction.

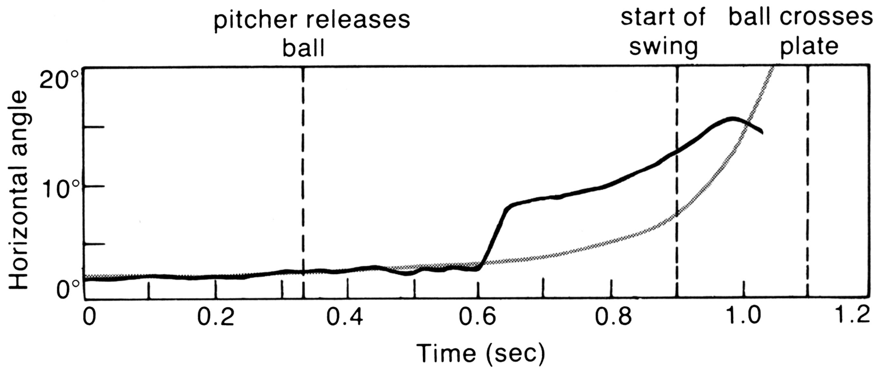

FIGURE 2.

Eye position as measured from one subject by Bahill and LaRitz.[17] The subject makes a saccade toward the plate (at ~0.60 seconds on the *x* axis) relatively early in the pitch trajectory and therefore eye position matches ball position shortly before the ball crosses the plate. Reprinted with permission from Bahill AT, LaRitz T. Why can't batters keep their eyes on the ball. Am Sci 1984;72:249-53. ©1984 Sigma Xi, The Scientific Research Society.

Equipment

Pitching Machine

The subjects viewed tennis balls projected from a pneumatic pitching machine (Flamethrower; Accelerated Baseball Technologies, Barrington, IL) (Fig. 3). The end of the pitching machine tube was 44.58 ft from the subjects. The tennis balls were marked with all black (22 balls) or all red (27 balls) numbers. Various publications mention the use of balls marked with colored patches or numbers.[33–35] Different tasks are used with the marked balls. Requiring subjects to identify the markings on pitched balls could facilitate gaze tracking by drawing attention to the balls.

We recorded (1000 Hz) the rotation of three pitched balls over the first 1 to 2 ft using a handheld camera (Exilim EX-ZR100; Casio, Tokyo, Japan). We found that the ball was rotating very little initially. Flankers around a (central) moving object can reduce one's ability to identify the central object,[36] and ball rotation (should it occur) in our case could exacerbate this effect.

The pitching machine was placed at the top of a 5-ft ladder supported by a platform. A polyvinyl chloride tube extended from the pitching machine and was supported by a tripod.

A preliminary test was run to assess the precision of the pitching machine. Fifty-six pitches were projected toward a ball stop from a distance of 60.5 ft. All of these pitches struck the stop within an area 16.5 inches high by 15 inches wide.

To make accurate gaze calculations, it was necessary to know the position of the ball at various points of the trajectory. Those data on the time required for the pitch to traverse various distances were measured as described in Appendix A (available at http://links.lww.com/OPX/A156). The distances at which the recordings were made and the resultant (mean) elapsed times for pitches to traverse these distances are shown in Table 1.

FIGURE 3.

The pneumatic pitching machine. A color version of this figure is available at www.optvissci.com.

TABLE 1.

Time (in milliseconds) required for a tennis ball to traverse specified distances and corresponding mean linear velocities for each distance

Test distance, ft	Measured time (SD), ms	No. trials	Linear velocity, ft/s
0	0	0	0
10	84 (1)	33	119.05
20	165 (2)	30	121.21
30	254 (2)	29	118.11
35.58	305 (5)	39	116.66
39.58	341 (3)	25	116.07
43.58	379 (4)	16	114.99

The number of trials indicates the number of pitches from which data were gathered.

The mean linear velocity of the pitch was 112 ft per second (76 miles per hour). Linear regression was applied to these data (distance traversed vs. time), and the correlation coefficient (r) of this fit was 0.995. Given the high temporal precision of the Flamethrower during the main experiment, ball position was monitored with a photocell (Appendix A, available at http://links.lww.com/OPX/A156) only as the ball exited the pitching machine tube.

Table 2 lists the linear distance the ball traversed and the corresponding visual angle for a viewing distance of 1.55 ft from the center of the plate. The values in the table associated with the 44.58-ft distance were obtained by calculation using the curve fit (distance vs. time) described above.

Head and Eye Movement Monitoring

Subjects were permitted to stand in a right-handed or left-handed batting stance. Eye movements were recorded using an eye tracker from ISCAN Incorporated (Burlington, MA). The ISCAN is an infrared video pupil tracker that measures the position of the eye in the orbit. The ISCAN cameras were affixed to a tight-fitting goggle. This system can measure both vertical and horizontal eye position, but only horizontal values were recorded in this study. Only those data from the left eye were analyzed. Because the pitch followed a parabolic trajectory (6-degree drop at 8 ft and 21-degree drop at 4 ft from the plate), it is possible that the eyes were moved vertically. Therefore, we assessed the cross talk (horizontal artifacts resulting from vertical movements) of an ISCAN as described in Appendix B (available at http://links.lww.com/OPX/A156). We conclude that any artifacts caused by cross talk were not likely to be more than about 2 degrees.

The spatial resolution of the ISCAN is at least 15 arc minutes. In a separate experiment (Appendix C, available at http://links.lww.com/OPX/A156), the mean difference between angular values obtained from the ISCAN were determined to be (on average) within 1 degree of measurements made with a search coil. The SD (device precision) of these differences was less than 1 degree. The update rate of the eye tracker was set at 120 Hz, which resulted in a sufficient range of angles over which eye movements could be measured.

To synchronize those data from the ISCAN with those data from the photocell at the end of the pitching machine tube (and therefore to relate these ISCAN data to ball location) and those data from the head tracker (described below), the digital ISCAN signals were converted to analog using a digital-to-analog converter. These analog signals were then fed into an 11-bit analog-to-digital converter (ADC) (USB-1208FS; Measurement Computing, Norton, MA) that was also used to record signals from the photocell and the head tracker. Each device was recorded at a rate of 2000 Hz. The ADC would record a signal from each device in succession (0.17 milliseconds between channels), then the recording process would repeat. Thus, the ISCAN was oversampled. The ISCAN data were therefore smoothed using an averaging filter (described below).

Once the ISCAN was placed on the subject, a visorless batting helmet was placed on the subject. A head tracking device was fastened tightly to the top of the helmet. The head tracker was a 3DM-GX1 from MicroStrain (LORD Corporation, Williston, VT). This device allows for horizontal (yaw), vertical (pitch), and tilt (roll) head rotation measurements, although we recorded only horizontal movements.

To assess potential artifacts in the MicroStrain measurements from cross talk, we mounted the device on a gimbal (Fig. 4). The

TABLE 2.

Change in visual angle between the pitched ball and the subject at elapsed times of interest

Time in trajectory, ms	Distance ball has traveled, ft	Change in visual angle from start, degrees	Relative angular velocity, degrees per second
0	0	0	0
150	17.5	1.4	9.3
200	23.3	2.4	20.0
250	29.2	4.1	34.0
300	35.0	8.2	82.0
341	39.58	16.0	195.1
381	44.58	87.97	1799.3

The change in visual angle was calculated assuming an individual's glabella was a distance of 1.55 ft from the center of the plate.

FIGURE 4.

The gimbal to assess cross talk with the MicroStrain tracker. A color version of this figure is available at www.optvissci.com.

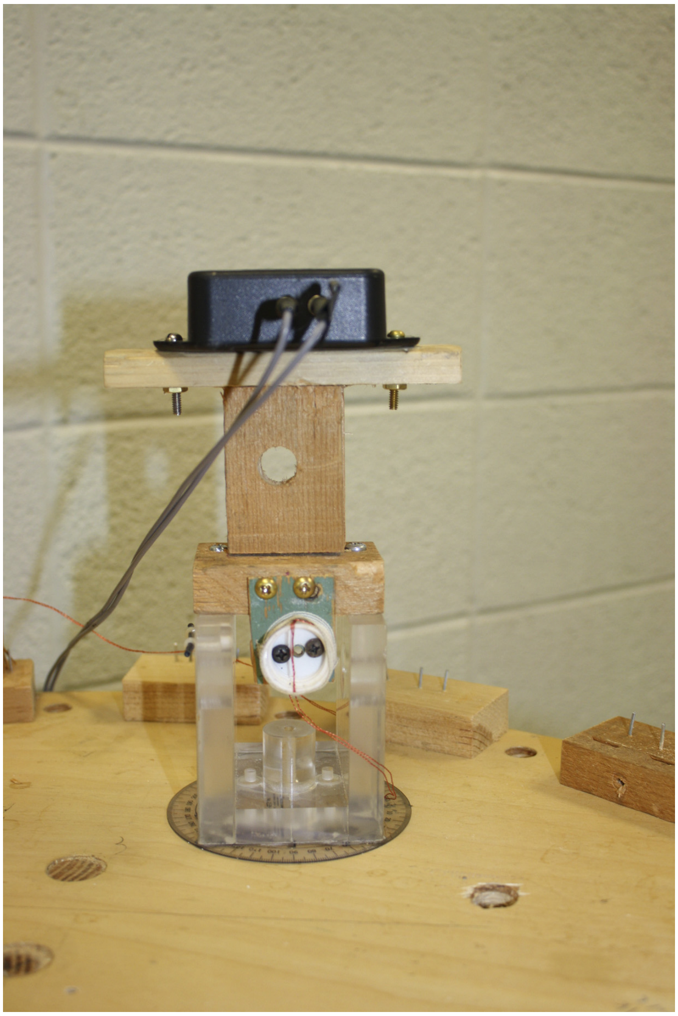

FIGURE 5.
Device used to determine the accuracy of the MicroStrain head tracker (Referenced in Appendix D; available at http://links.lww.com/OPX/A156). A color version of this figure is available at www.optvissci.com.

gimbal was arranged such that the horizontal axis was rotated horizontally when the apparatus was rotated about its vertical axis (Fick arrangement[37]). The apparatus was rotated to various horizontal angular positions. At each of these horizontal positions, the MicroStrain was rotated vertically and the horizontal analog output was read. No horizontal artifacts were noted.

In a separate experiment (see Appendix D, available at http://links.lww.com/OPX/A156; Fig. 5), the mean difference between angular values obtained from the MicroStrain was determined to be (on average) within 1 degree of measurements made with a search coil. The SD of these differences was less than 1 degree.

Finally, in a separate experiment (Appendix E, available at http://links.lww.com/OPX/A156), it was shown that slippage of the batting helmet was unlikely to significantly influence those data from the MicroStrain.

Analog data from the MicroStrain were fed into the same 11-bit ADC as that into which the ISCAN and the photocell at the end of the pitching machine tube were fed. In this way, the ISCAN, photocell, and MicroStrain analog signals could be recorded in synchrony.

The update rate of the MicroStrain was 100 Hz, whereas the MicroStrain analog data were recorded by the ADC at 2000 Hz. Thus, the MicroStrain was also oversampled. It was necessary to smooth those data from the MicroStrain with an averaging filter (described below).

Because the MicroStrain calibration will not vary between subjects, a single calibration factor relating horizontal angular rotation to MicroStrain output was determined for all subjects while the MicroStrain device was mounted on a protractor. The accuracy of this calibration factor was tested by comparing values of horizontal rotation obtained from the MicroStrain with those from a search coil (Appendix D, available at http://links.lww.com/OPX/A156).

On the other hand, the calibration factor of the ISCAN does vary between individuals. To calibrate those ISCAN data, a two-point calibration (targets 40 degrees apart) was used for each subject. The calibration procedure was evaluated as shown in Appendix F (available at http://links.lww.com/OPX/A156).

Experimental Design

After the informed consent process and the visual acuity measurement, the eye and head tracking equipment was placed on the subject. The subjects held a baseball bat throughout the experiment to more closely approximate a true batting stance. They were told not to swing the bat. A measurement from the middle of each subject's forehead to a vertical line from the center of the plate was made. This was done to calculate the visual angle of the ball throughout the pitch trajectory. The mean distance was 1.55 ± 0.31 ft.

Next, the eye tracker calibration measurements were made. Each subject was then shown two tennis balls (Fig. 6). One tennis ball had a number written on it in six locations in black (numbers were ~18 mm high and 2 mm wide). The other ball was marked in the same fashion but with red. The subjects were told to call out the color (black or red) and number (0 to 8) on the balls released from the pitching machine. The subjects were told to guess if they were unsure.

FIGURE 6.
An example of the tennis balls used as targets for this experiment. A number was written with a permanent marker on six locations of each ball. For an individual ball, all markings were the same number, ranging from 0 to 8, and the same color (red or black). A color version of this figure is available at www.optvissci.com.

Forty-nine pitches were presented in two back-to-back sessions. To record each subject's color/number naming responses, one investigator randomly placed the tennis balls into the pitching machine one by one and recorded the ball's color and number. Subject responses were recorded by another investigator.

Every effort was made to ensure that subjects did not see the balls as they were placed in the pitching machine. Furthermore, we observed the subjects and in only one case was it evident that a subject was attempting to view the ball after it struck the back-stop.

Data Analyses

Summary of Data Collection

Data could be analyzed for 17 of the 18 subjects. All of those data from one subject and a single run (49 pitches) from two other subjects could not be analyzed because the analog outputs from one or more devices were recorded improperly.

Variability in the ISCAN Calibration Factors

The mean ISCAN calibration factor for all 17 subjects was calculated. The calibration factor for all of the subjects except one fell within ±17% of the mean. Those data from the individual with the outlying calibration factor were discarded (so 16 subjects remained).

Initial Head and Eye Positions

We assumed that subjects were looking at or near the pitching machine tube when the ball was released from this tube. We did not instruct subjects specifically on where to look, but we believe that our assumption regarding the initial gaze position is valid for the reasons discussed in Appendix G (available at http://links.lww.com/OPX/A156). However, after the analyses described in Appendix G, we discarded one subject's data, leaving 15 subjects.

Objective Assessment of Eye Movement Amplitude, Head Movement Amplitude, and GE

Those raw data from the eye and head trackers were analyzed using a custom computer program. Those data from the eye and head were calibrated and then smoothed using a 40-point averaging filter. Next, these data were corrected for temporal delays. The accuracy of the compensation for these delays was assessed as described in Appendices C and D.

Next, the angular changes in eye and head positions from the beginning of the pitch to six elapsed times after the pitch was released were calculated. The times in the pitch trajectory chosen for analysis were 150, 200, 250, 300, 342 (~4 ft short of the plate), and 382 milliseconds (full distance). The elapsed time of 342 milliseconds was chosen because, at that time, the ball is at a distance similar to that at which the MLB player (5.5 ft) in the Bahill & Laritz study[17] could no longer effectively track the ball. The 1-millisecond discrepancy between the 342- and 382-millisecond values (Table 3) and the 341- and 381-millisecond values shown in Table 2 occurred because we originally performed measurements of the time for the ball to traverse various distances using a timing window that we designed. From these data, we fit a function to the distance traversed versus elapsed time curve. This curve was used to determine the elapsed times at distances of interest in the current experiment. Later, we used a commercially available ballistic timing window (Appendix A, available at http://links.lww.com/OPX/A156) and obtained those data reported in Tables 1 and 2.

Through visual inspection of the GE and eye movement data, some pitches were discarded because of blinks. ISCAN signals for the corresponding pitch were graphed to ensure that a blink was present. After this, 1335 pitches out of the 1372 pitches recorded could be analyzed.

Angular changes in eye and head rotation were then added together to obtain the angular change in horizontal gaze from the beginning of the pitch to each of the elapsed times of interest. Finally, the difference between the angular change in gaze position and the angular change in ball position at elapsed times of interest was calculated to obtain the UGEs and signed GEs. A UGE is the best indicator of the overall accuracy of gaze tracking, whereas a signed GE best reveals the tracking strategy (lag or lead).

The mean changes in head position, mean changes in eye position, mean signed GEs, and mean UGEs are shown at elapsed times of interest for all subjects combined in Table 3 and Fig. 7. The mean changes in head position, mean changes in eye position, and mean signed GEs at four elapsed times for individual subjects are shown in Table 4.

RESULTS

Visual Acuity Data

Mean logMAR visual acuity for all 18 subjects was 0.03 (0.11) RE and 0.06 (0.12) LE. One subject had an acuity of 0.3 logMAR (20/40) in one eye. No subject had a visual acuity worse than 0.3 logMAR.

TABLE 3.
Overall (combined) mean head rotation, mean eye rotation, mean signed gaze error, and mean unsigned gaze error for various times of the pitch trajectory

Time in trajectory distance traveled	0 ms 0 ft	150 ms 17.5 ft	200 ms 23.3 ft	250 ms 29.2 ft	300 ms 34.9 ft	342 ms 40.6 ft	382 ms 44.6 ft
Mean eye movement (SD), degrees	0	0.2 (0.9)	0.7 (1.4)	1.1 (2.1)	1.6 (3.1)	3.4 (5.2)	12.9 (19.4)
Mean head movement (SD), degrees	0	1.0 (1.1)	2.0 (1.6)	3.6 (2.5)	6.4 (3.8)	10.0 (5.8)	14.6 (8.9)
Signed gaze error (SD), degrees	0	–0.0 (0.7)	0.5 (1.1)	1.3 (2.2)	1.0 (3.0)	–5.4 (7.4)	–60.5 (21.5)
Unsigned gaze error (SD), degrees	0	0.6 (0.4)	0.9 (0.7)	2.0 (1.6)	2.5 (1.9)	7.4 (5.4)	61.1 (19.5)

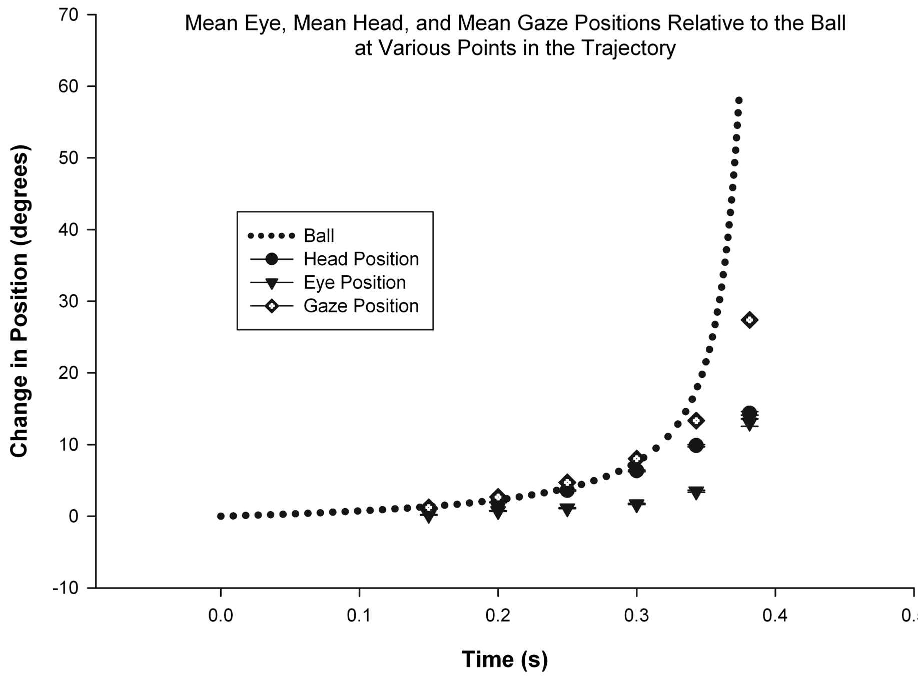

FIGURE 7.
Mean eye rotation, mean head rotation, and mean signed gaze error versus time for all subjects.

Color/Number Naming Performance

Color and number naming data were available for 14 of the 15 subjects from whom objective data were analyzed. The mean color naming accuracy was 70.4 ± 11.9%. A color naming percentage of 75% would need to be achieved in this two-alternative forced choice task to conclude that subjects could discern the color above chance. Overall, subjects were unable to reach 75%. The emblem printed on the balls (labeled in red and black) may have been a confounding variable, leading to worse performance than might be expected otherwise. The number naming accuracy was 11.6 ± 9.0%. For number naming, the subjects performed at chance (11%). We conclude that subjects were unable to resolve the numbers.

Combined Head Movement, Eye Movement, and Gaze Data

Overall, those mean data from all subjects combined (Table 3; Fig. 7) show the following. First, the head tracked the target throughout much of the pitch trajectory. Second, the eye movement amplitude remained nearly constant until very late in the trajectory. Finally, gaze was directed near the target throughout much of the pitch.

Relationship between Eye and Head Tracking Values for Individual Subjects

If the RVOR is invoked during head-eye pursuit, a negative relationship between the amplitudes of head and eye movement is expected. Preliminary inspection demonstrated such a relationship. However, at an elapsed time of 300 milliseconds, there were cases where the mean eye movement amplitude was nearly equal to or even exceeded the mean head movement amplitude for some subjects (Table 4). This behavior is not consistent with a simple RVOR-related eye movement.

A one-way analysis of variance (ANOVA) at an elapsed time of 300 milliseconds demonstrated significant differences in head movement amplitude between subjects ($p < 0.001$). Given the variability in head (and eye) tracking strategy between subjects demonstrated in Table 4 and verified by the ANOVA, we wanted to determine whether a common equation could be derived relating eye movement to head movement. We plotted the difference between head movement amplitude and eye movement amplitude against head movement amplitude. If the RVOR was fully invoked (no RVOR suppression), then the slope of this line would be 2.0. Alternatively, if the RVOR were completely suppressed, then the slope of the line would be 1.0.

The results are shown in Fig. 7. There was a very strong linear relationship between the difference in head and eye movement amplitudes and the head movement amplitude until an elapsed time of 382 milliseconds. At elapsed times of 342 and 382 milliseconds, large negative ordinate values appeared. These data points represent large eye movements (presumably saccades). As the elapsed time increased from 150 to 342 milliseconds, the slope of the regression lines remained similar (although <2) while the y intercept steadily increased. Thus, early in the pitch, trajectory tracking is primarily accomplished through the (partially suppressed) RVOR. The RVOR suppression is on the order of 30 to 40% at elapsed times of 200 to 300 milliseconds. As the elapsed time increases, subjects superimpose an eye movement in the direction of the pitched ball on the RVOR-related eye movement (the y intercept reflects this eye movement). This eye movement increases in size as the elapsed time increases.

Relationship between Head Movement and Gaze

A question of interest was whether the differing head movement amplitudes led to changes in the UGEs and signed GEs. A

TABLE 4.

Mean head movement, mean eye movement, and mean signed gaze errors for individual subjects at various times of the pitch trajectory

	150 ms			250 ms			300 ms			342 ms		
Subject	Head	Eye	Signed gaze error	Head	Eye	Signed gaze error	Head	Eye	Signed gaze error	Head	Eye	Signed gaze error
1	0.0 (0.9)	0.8 (1.1)	–0.7 (0.5)	1.6 (1.5)	2.4 (1.7)	–0.7 (1.1)	3.3 (2.0)	3.4 (2.0)	–2.1 (1.5)	5.4 (2.3)	4.9 (2.1)	–12.8 (1.9)
2	1.3 (0.8)	0.6 (0.6)	1.0 (0.6)	3.9 (1.5)	2.4 (1.2)	3.7 (0.8)	6.2 (2.2)	4.1 (1.6)	5.2 (1.2)	8.2 (3.1)	6.2 (2.2)	0.7 (1.7)
3	0.7 (0.6)	0.4 (0.6)	–0.2 (0.6)	2.1 (1.1)	1.7 (0.9)	0.4 (0.8)	3.3 (1.7)	2.2 (1.2)	–1.1 (1.3)	4.4 (2.5)	2.1 (1.4)	–11.2 (2.0)
4	0.7 (0.5)	0.8 (0.6)	0.4 (0.5)	3.2 (1.1)	3.2 (1.1)	3.2 (1.0)	6.6 (2.0)	4.8 (1.7)	5.3 (1.6)	11.7 (3.4)	6.7 (2.8)	1.7 (2.2)
5	0.1 (0.8)	1.0 (0.7)	–0.1 (0.7)	1.6 (1.1)	3.2 (1.0)	1.2 (1.0)	4.4 (1.7)	4.6 (1.3)	2.0 (1.5)	9.2 (2.6)	5.7 (1.7)	–3.7 (2.0)
6	1.2 (1.0)	0.3 (0.7)	–0.4 (0.7)	4.0 (2.0)	1.9 (1.5)	0.5 (1.1)	6.6 (2.9)	2.6 (2.1)	–1.2 (1.6)	9.0 (3.9)	3.6 (3.0)	–13.9 (2.3)
7	1.3 (0.9)	–0.2 (0.5)	–0.2 (0.6)	4.9 (1.7)	0.5 (1.5)	1.4 (0.7)	8.4 (2.3)	0.7 (1.9)	1.4 (1.0)	12.0 (3.0)	1.9 (2.8)	–6.7 (2.8)
8	2.8 (1.2)	–1.0 (0.9)	0.1 (0.5)	7.9 (2.2)	–1.9 (1.9)	1.4 (0.8)	12.6 (2.9)	–1.9 (2.4)	1.8 (1.2)	18.4 (3.7)	1.2 (5.0)	–3.6 (5.6)
9	1.8 (0.8)	–0.4 (0.6)	0.5 (0.5)	5.9 (1.2)	–1.4 (1.0)	4.4 (2.1)	10.2 (1.5)	–2.8 (1.3)	1.9 (1.2)	15.3 (1.8)	–3.6 (2.0)	–3.4 (1.9)
10	0.8 (0.8)	0.2 (0.6)	–0.2 (0.4)	4.4 (2.4)	–0.1 (1.8)	0.5 (1.1)	9.6 (4.4)	–1.2 (2.2)	1.3 (3.0)	18.3 (6.6)	0.5 (3.3)	–0.3 (7.2)
11	0.2 (0.3)	0.9 (0.4)	0.3 (0.4)	1.3 (0.5)	3.3 (0.6)	2.1 (0.6)	3.0 (0.7)	5.5 (0.7)	3.8 (0.8)	6.7 (1.4)	11.4 (9.2)	5.3 (9.1)
12	0.6 (0.6)	0.4 (0.5)	–0.1 (0.6)	2.8 (1.3)	1.5 (1.2)	1.0 (0.7)	4.9 (2.2)	2.5 (1.9)	1.0 (1.0)	7.6 (3.4)	4.4 (2.4)	–5.3 (2.9)
13	1.2 (1.1)	–0.4 (1.2)	–0.4 (0.4)	3.7 (1.7)	–0.3 (1.9)	0.2 (3.5)	5.4 (2.2)	0.2 (2.4)	–1.6 (0.8)	7.2 (2.9)	1.3 (3.1)	–10.6 (1.1)
14	1.2 (1.1)	–0.2 (0.9)	–0.3 (0.5)	4.0 (2.1)	0.3 (1.7)	0.4 (1.2)	6.7 (3.0)	0.3 (2.1)	–0.3 (1.7)	9.9 (4.0)	3.3 (4.2)	–6.3 (4.8)
15	0.2 (0.3)	0.5 (0.3)	–0.7 (0.4)	0.8 (0.5)	1.6 (0.5)	–1.7 (0.5)	1.5 (0.8)	2.4 (0.7)	–3.8 (0.85)	2.3 (1.1)	4.2 (2.7)	–14.1 (3.1)

The SD of these means is included in all cases.

one-way ANOVA demonstrated that there were significant differences in signed GEs and UGEs between subjects at 300 milliseconds ($p < 0.001$).

Linear regression of signed GE and UGE versus head movement was performed at all elapsed times of interest. The results are shown in Table 5 and demonstrate that the signed GEs and UGEs could not be reliably predicted from the head movement amplitude.

DISCUSSION

Gaze Tracking Strategy

Those tracking data obtained from the MLB player by Bahill and LaRitz[17] (Fig. 1) are very similar to our mean data (Table 3; Fig. 7). In both cases, the head is moved in the direction of the ball; whereas for much of the pitch trajectory, the eye position remains relatively constant. Late in the pitch trajectory, a larger eye movement is made in the direction of the ball. On the other hand, these data are only partially consistent with those obtained by Mann et al.[28] on elite cricket players. The elite players in the study by Mann et al.[28] directed the head toward the pitched ball until just before bat-ball contact. At that time, they made an anticipatory saccade to the location where bat-ball contact was likely to be made.

Mann et al.[28] have pointed out that visuomotor tasks such as batting are said to be controlled egocentrically. Therefore, maintaining the head in a relatively constant direction compared with the ball may help in hitting the ball. However, our subjects were not swinging at the ball, so it is difficult to know why our subjects would couple their head movement to the ball. It could be that our subjects moved their heads as if they were hitting, but this notion remains speculative until measurements are made during baseball batting. Certainly, this behavior is not predicted by studies on catching fly balls, where it has been shown that subjects move primarily the eyes when tracking fly balls, but they move the eyes *and* the head when attempting to catch fly balls.[38–40]

The overall gaze tracking behavior of our subjects was not consistent with the gaze tracking behavior of the elite cricket players in the study by Mann et al.[28] The elite players in Mann et al.[28] tended to make an anticipatory saccade so that gaze was directed to the location of the ball around the time the player made contact with the ball.

There are at least five potential reasons for the difference in gaze tracking behavior between our subjects and those of Mann et al.[28] First, it is possible that the color/number naming task led our subjects to maintain gaze continuously on the target. Second, our subjects were not hitting the ball. Third, the trajectory and timing of the pitches thrown by our pitching machine were very predictable, and anticipatory saccades may be more common when the trajectory is unpredictable.[17] Fourth, our subjects were accomplished players but not necessarily elite. Anticipatory saccades may be less common in nonelite players.[28] Finally, anticipatory saccades may be less common in baseball compared with cricket because, unlike cricket, in baseball the ball does not bounce before bat-ball contact.

Variability between Subjects

Head and Eye Movement Relationship

The one-way ANOVA on head movement amplitude demonstrated significant differences between subjects. However, when linear regression was applied to the difference between head movement amplitude and eye movement amplitude and the head movement amplitude, a strong correlation was found (Fig. 8). These results suggest that subjects applied a common strategy consisting of partial RVOR suppression combined with an eye movement in tracking the targets.

Gaze Tracking Errors and Head and Eye Movement Amplitudes

The individual mean GEs demonstrate that gaze was close to the ball (within about ±5 degrees) up to an elapsed time of

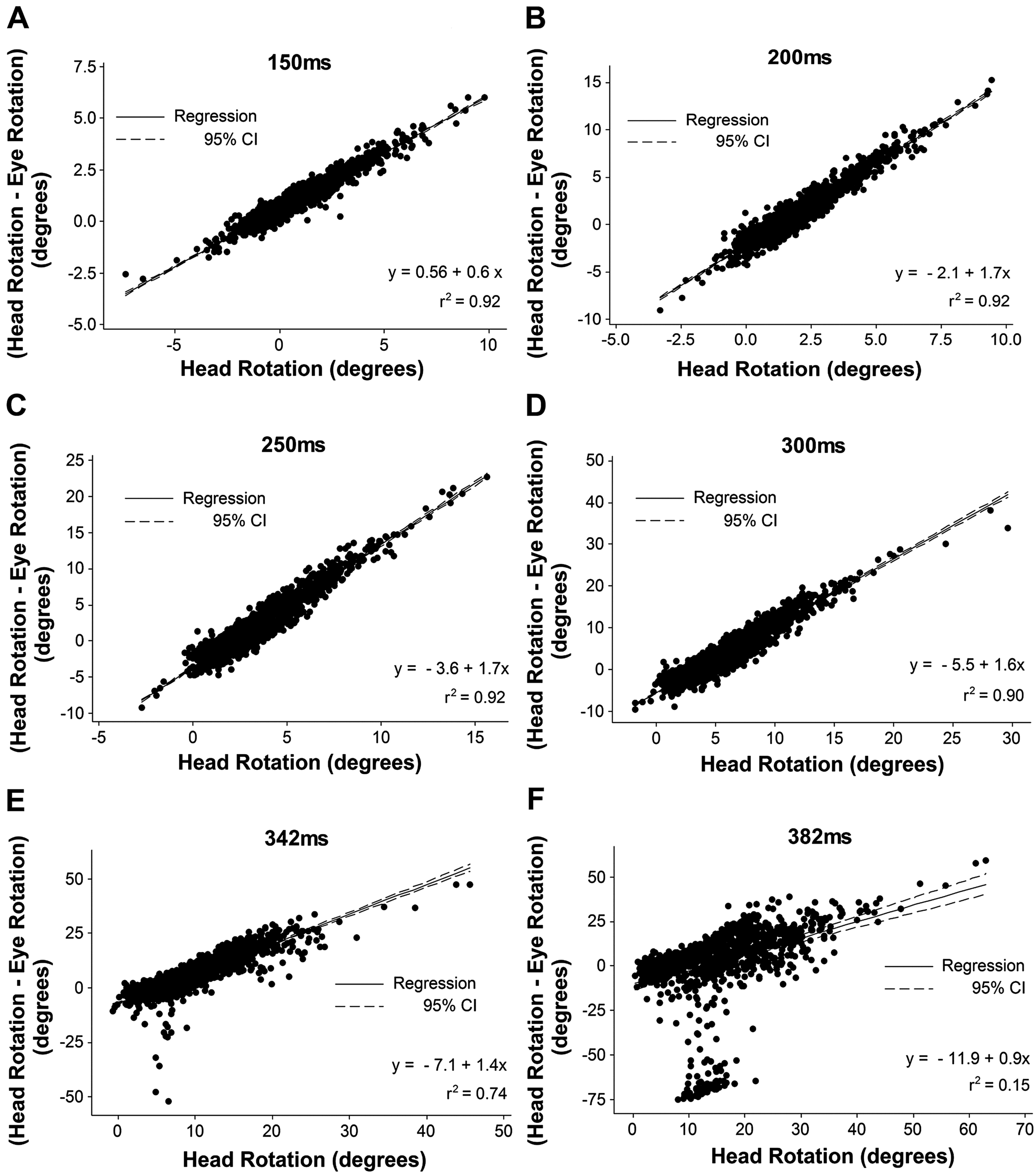

FIGURE 8.

(A–F) Regression plots of (head rotation – eye rotation) versus (head rotation) for various elapsed times in the pitch trajectory. The dashed lines show the 95% confidence intervals for the regression fits. (A) elapsed time = 150 milliseconds; (B) elapsed time = 200 milliseconds; (C) elapsed time = 250 milliseconds; (D) elapsed time = 300 milliseconds; (E) elapsed time = 342 milliseconds; (F) elapsed time = 382 milliseconds.

300 milliseconds for all subjects. Anticipatory saccades were not apparent in the individual mean data.

The one-way ANOVA on UGE and signed GE demonstrated significant differences between subjects. However, regression analyses demonstrated that the signed GEs and UGEs did not correlate well with the head movement amplitude (Table 5). Taken together, these analyses suggest that the differences in GEs between subjects can only be accounted for by the combination (i.e., addition) of the head movement and eye movement amplitudes.

TABLE 5.
Correlation between signed gaze errors and head rotation and unsigned gaze errors and head rotation

Signed gaze vs. head	Slope	r^2	p
150 ms	$y = -0.4 + 0.3$ (head)	0.21	<0.001
200 ms	$y = 0.1 + 0.2$ (head)	0.14	<0.001
250 ms	$y = -0.2 + 0.4$ (head)	0.24	<0.001
300 ms	$y = -1.2 + 0.3$ (head)	0.19	<0.001
342 ms	$y = -11.1 - 0.6$ (head)	0.21	<0.001
382 ms	$y = -76.2 + 1.1$ (head)	0.20	<0.001
Unsigned gaze vs. head			
150 ms	$y = 0.6 + 0.0$ (head)	0.00	0.6
200 ms	$y = 0.8 + 0.1$ (head)	0.03	<0.001
250 ms	$y = 1.2 - 0.2$ (head)	0.09	<0.001
300 ms	$y = 2.42 + 0.0$ (head)	0.00	0.7
342 ms	$y = 10.4 - 0.3$ (head)	0.12	<0.001
382 ms	$y = 76.9 - 1.1$ (head)	0.24	<0.001

Summary of Variability Analyses

Some behaviors were similar between subjects, and some behaviors varied between subjects. In terms of similarities, subjects maintained gaze relatively close to the ball throughout much of the pitch trajectory (i.e., anticipatory saccades were not apparent). It is not clear at this time whether the lack of anticipatory saccades is related to the methods applied in this experiment (e.g., no batting, predictable target).

On the other hand, differences between subjects were also evident. The mean head movement amplitudes varied as did the mean eye movement amplitudes. Furthermore, the mean GEs varied somewhat between subjects.

Overall, it is clear that there are intersubject differences in tracking strategy and GE. Whether these differences could be related to on-field hitting performance or whether these differences would be evident when subjects attempt to hit the ball is unknown. At the moment, the notion that there is a standard method by which the head and eye should be coordinated for gaze tracking in baseball is not supported by these data.

CONCLUSIONS

In summary, on average, these Division 1 college baseball players applied a strategy similar to that of the MLB player of Bahill and LaRitz.[17] These behaviors are not consistent with the results of studies on tracking fly balls, where the eyes are moved to a much greater extent than the head.[38–40]

Anticipatory saccades were not apparent in our data. Studies in which eye, head, and gaze tracking strategies of elite baseball batters who are attempting to bat balls under game conditions (unpredictable stimuli) are required to determine whether anticipatory saccades are common in baseball. Furthermore, studies in which baseball players swing at pitched balls would aid us in determining whether the behaviors found in this study and the variability in these behaviors apply to on-field performance. If the measured behaviors while viewing pitches are similar to those behaviors during batting, then subjects could practice gaze tracking even when hitting is impractical.

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APPENDICES

Appendices A–E are available at http://links.lww.com/OPX/A156.

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