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Timing Differences in Eye-Hand Coordination Between Experienced and Inexperienced Tennis Players

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ABSTRACT

Background: Tennis is one of the most popular sports in the U.S. However, there is relatively little objective investigation of the underlying body and racquet dynamics. In the present study, timing differences in eye, head, and racquet motions during the tennis stroke were investigated.

Methods: Two experienced and two inexperienced young-adult tennis players participated in this pilot study. The task was to hit the center of a multi-ring bull's-eye target located 3 meters away at a height of 1.37 m. Each subject performed 40 forehand and 40 backhand trials. The eye, head, and racquet motions were recorded via wireless sensors. In addition, a digital video recorder was used to record the trials for offline detailed analysis.

Results: In all subjects, head movement initiation occurred prior to both eye motion and racquet impact for both the forehand and backhand strokes. In addition, eye movement initiation occurred before racquet impact in experienced players, but after racquet impact in the inexperienced players.

Conclusions: Head rotation may be an important component in the neuro-motor sequence of movements for generating body torque to provide power in the groundstroke. Also, the experienced player may use a more optimal, pre-programmed strategy for attaining and maintaining both consistency and accuracy. These new findings provide insight into how training of eye-hand coordination is revealed in the timing differences during the racquet-impact phase of the groundstroke.

Keywords: eye-hand coordination, neuro-motor control, pre-programmed, sports biomechanics, tennis

Introduction

Eye-hand coordination and proper head and body positioning are essential components of a good tennis stroke. However, despite a general consensus on what dictates a proper form of play, a level of differentiation in performance can be observed across players.[1] Since the movements of players are generally similar, strategic differences in ability must be rooted elsewhere. As such, it is essential to examine various forms of information processing and stimuli that lead to quantifiable changes in performance.

Quantitative analysis of the timing between head and eye motions and between eye and racquet motions can provide important insights into the appropriate timing and coordination for a "good" tennis stroke. In the present pilot study, timing differences between experienced and inexperienced individuals, as well as between accurate and inaccurate tennis shots, were quantified using objective recording techniques.

There has been substantial growth and interest in recent years in the study of sports biomechanics and its implications on the performance of the human body.[2] The results of such studies have been used to improve athletic performance, as well as to diminish the chances of injury. Biomechanical research in athletics has focused primarily on physiological responses during athletic motions, kinematics of joint motions, and modeling and simulation of body components.[3-5] Findings have provided important insights into areas such as oculomotor dynamics and neuro-muscluar control during athletic movements. For example, a close examination of gaze behavior in basketball shooting has led to identifying visual search strategies, as well as differences between expert and novice athletes.[6] Furthermore, researchers have found that players use a form of pre-programmed visual-motor control in the baseball swing.[7] While a great deal has been learned regarding the biomechanics of the tennis stroke,[8] there have been relatively few quantitative studies of eye, head, and racquet motions during the tennis stroke.[5]

Tennis is a sport that requires the coordinated motions of many different body components.[8-10] With slight adjustments in arm movements and subtle changes in wrist position, a shot can be altered to tailor the needs of a given scenario. In the modern game of tennis, there are seven basic types of shots: serve, groundstroke (forehand and backhand), lob, slice, smash, and volley.[8] Additionally, players can apply various techniques to modify the flight pattern of the ball as it is hit by imparting topspin, backspin, etc.; this leads to tremendous variation in how the seven basic shots can be modified and employed during a game. Traditionally, the groundstroke movement sequence is subdivided into essentially four stages of motion: preparation, backswing, forward stroke, and follow-through.[8] A more compact way to assess the stroke is to divide it into two phases: the Acquisition Phase (AP) followed by the Strike Phase (SP). While a multitude of topics can be discussed regarding the biomechanics of tennis, the present research focuses on the biomechanics involved in the groundstroke, i.e., forehand and backhand shots.

Proper execution of a tennis stroke requires sound fundamentals. Many tennis theorists and professionals advise players to minimize eye and head movements as much as possible during a groundstroke, and furthermore emphasize the effectiveness of a fluid follow-through motion.[11-12] For such movements to be successfully applied during an ongoing match, researchers have developed a "vision technique" that the players can employ.[13] Conventionally, players are instructed to "see" or to "watch" the ball as it makes its way into the string bed of the racquet, regardless of its origin. The proposed vision technique instructs the player to look for impact not at the front but rather at the back of the racquet. This technique in essence provides the player with more control of the game, as the mental focus changes from waiting for the ball to hit the racquet to that of the racquet hitting the ball. Among current professional players, this technique seems to be prominently used by Roger Federer and Rafael Nadal.[13]

Methods

A. Subjects

Four Rutgers University undergraduate students (3 males and 1 female) ranging in age from 19 to 22 years participated in the study. Two had more than 5 years of intramural competitive tennis experience, and the other

Figure 1: *Multi-ring bull's-eye target*

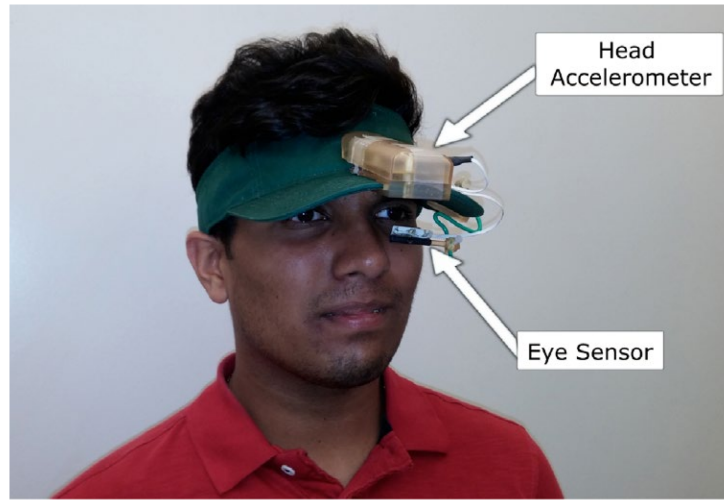

Figure 2: *Subject wearing visor with attached eye and head movement sensors*

two had less than 1 year of general tennis experience. Their distance visual acuity (20/20 with correction binocularly), lens flipper (8 cycles/min, binocularly), prism flipper (15 cycles), and randot stereoacuity (20-30 sec of arc) were all within normal limits. All subjects were right-handed and were in good general health. The subjects provided informed consent prior to the experiments. The study was approved by the Rutgers University Institutional Review Board.

B. Apparatus

A multi-ring bull's-eye target was used to measure accuracy of the subjects' shots. The target consisted of five rings with equally-spaced radial dimensions of 8.4 cm, so that the edge of the outer ring was 42 cm from the center (Figure 1). In terms of visual angles, each ring subtended 1.6 deg, so that the target's total radial extent was 8 deg. The colors of the ring were: yellow (innermost ring), red, blue, white, and black (outermost ring). The target was imprinted on a standard display board (91.4 cm by 121.9 cm), which was mounted on a support platform, so that the center of the target was 1.37 m above ground level. This height was chosen mainly because of the availability of a sturdy wooden platform used in previous golf studies in the laboratory, where the resulting height of the center of the target (1.37 m) was appropriately above the standard net height (0.914 m at the center and 1.067 m at the side posts). The distance between the target and the subject was 3 m.

To measure eye and head motions, the subjects wore a visor consisting of wireless biosensors that were used in a previous study[4] (Figure 2). The eye sensor uses an infrared reflection limbal tracking technique to measure horizontal eye rotation.[14] It has a resolution of 15 min arc, a linear range of ±25°, and a bandwidth of 200 Hz. The head sensor consists of an accelerometer in a circuit board mounted on the beak of the visor (Figure 2). The head position signal was estimated based on a control trial in which the subject performed several constant-speed sinusoidal head rotations about a vertical axis over a range of +/- 10 deg. Additionally, a wireless accelerometer unit was securely positioned on the handle of a tennis racquet (Head Crossbow 4) to measure the racquet motions[15-16] (Figure 3). The electronic signals from the eye, head, and racquet sensors were transmitted wirelessly to a circuit board connected via the USB port on a conventional laptop computer running a software program custom-designed by one of the co-authors (G.K. Hung). The entire recording system has a sampling rate of 100 Hz.[15,16] Lastly, to record the visual scene and the motions of the subjects during the tennis stroke, as well as to verify

Figure 3: *Experimental setup showing subject in preparation for a groundstroke to attempt to hit the center of the multi-ring bull's-eye target. The subject wore a visor with sensors for eye and head movements, while a sensor secured on the racquet handle was used to record racquet motions. In the lower-right foreground is the monitor showing the instantaneous traces of eye, head, and racquet motions as a function of time*

the accuracy of the target hits, a digital video recorder (Sony Handycam HDR-CX230) was used during the trials.

C. Experimental Procedure

The tennis groundstroke experiments were conducted in a laboratory environment over a two-week period. Each subject participated in a total of 4 sessions on two separate days, with 2 forehand-groundstroke sessions on day one and 2 backhand-groundstroke sessions on day two. During each session, the subject attempted 20 shots, while the eye, head, and racquet motions were recorded. In executing the shot, the subject held the tennis ball with the left hand at chest height, dropped the ball to the ground following the experimenter's verbal command, and as the ball returned towards its initial position, proceeded with the ground stroke. It should be noted that our earlier attempts at using a commercial air-flow ball batting tee (the Hit Zone Standard Tennis Practice Tee) resulted in inconsistent ball positioning due to the small fluctuations from the upward air flow. After each shot, the accuracy, i.e., the target ring that was hit by the tennis ball, was recorded manually. Throughout the duration of each session, the digital video recorder provided a visual recording for further analysis.

Score Keeping

Points were awarded for each individual shot based on which ring the tennis ball hit on the target. Hitting the central yellow ring yielded 5 points, red yielded 4, blue yielded 3, white yielded 2, black yielded 1, and anything off target yielded 0 points. The maximum score was 100 points for the 20 shots. Hence, the actual points for the session provided the percentage score for each subject. This provided an assessment of subject performance.

Data Analysis

The eye, head, and racquet-motion signals were displayed as time traces on graphs that were vertically aligned in a Microsoft Excel spreadsheet. This provided a means to determine and to compare the timing of initiation of the movements.

As the Excel graphs were quantitatively assessed, the video recordings were uploaded onto a separate laptop computer and reviewed on a frame-by-frame basis to determine the location of the target hits, as well as to observe changes in eye, head, and racquet motions. The videos were further analyzed using the Sony Vegas Pro 11 editing software. This allowed for simultaneous displays of close-ups of the subject's eye and head motions, with the traces displayed on the computer monitor, along with the original video image. This approach provides visual evidence to pinpoint the time of initial movements of the eye and the head, as well as the time of racquet impact with the tennis ball, with a temporal resolution of approximately 10 msec. The initiation times of the movements (in msec) were then input to a Microsoft Excel program. Differences in time between eye and head (Eye – Head) and eye and impact (Eye – Impact) were calculated. The averages of the 40 trials under each condition per subject were calculated.

Based on preliminary trials, it was found that the individual target rings did not

Table 1: Time Differences (msec) for Eye - Impact and Eye - Head

		IP1		IP2		EP1		EP2	
		Poor	Good	Poor	Good	Poor	Good	Poor	Good
Eye - Impact	Forehand	3	11	37	89	-25	-8	-121	-89
	Backhand	76	64	81	69	-84	-64	-156	-114
Eye - Head	Forehand	125	122	170	220	351	374	94	137
	Backhand	134	95	120	120	113	122	113	112

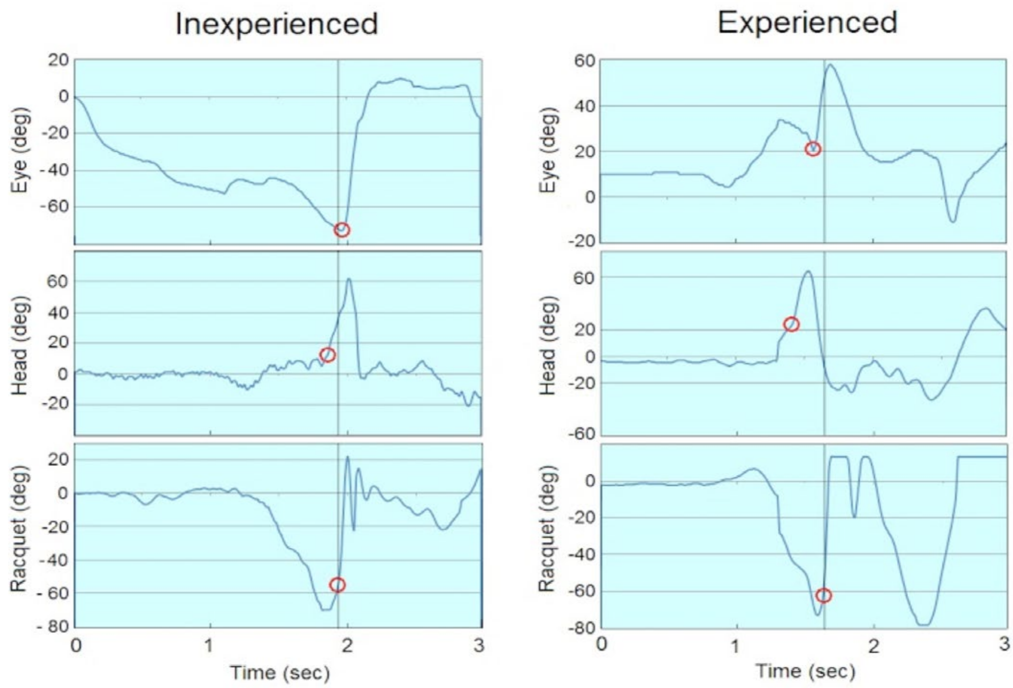

Figure 4: Typical time traces of eye, head, and racquet motions for forehand showing initiation of eye movements (a) after racquet impact for the inexperienced player, but (b) before racquet impact for the experienced player. Initiation of movements is indicated by red circles. Note that head motion occurs before both eye movement and racquet impact for both the inexperienced and experienced players. All movements were converted to degrees of angular rotation about their central axis of rotation. Subs IP1 and EP2.

provide sufficient resolution to distinguish any significant effects in timing differences. Therefore, the rings were grouped together, so that all hits in the inner rings (yellow, red, and blue) were considered "good" shots, and all hits in the outer rings (white, black, and off-target) were considered "poor" shots. The values of the timing differences between Eye – Head and Eye – Impact were averaged for both "good" and "poor" shots for each subject, and this served as the basis for comparison for the different stimulus conditions.

Results

A. Movement Comparisons of Representative Trials

Typical records of eye, head, and racquet motions for the forehand (Figure 4) and backhand (Figure 5) are shown for an inexperienced player (left panel) and an experienced player (right panel). The time of initiation for each movement is marked by a red circle. Initiation of eye motion occurred after the time of racquet impact in the inexperienced players, whereas it occurred prior to racquet impact in the experienced players. In contrast, initiation of head motion occurred prior to eye motion for both categories of players.

B. Across-Subject Analysis

Table 1 presents the averaged time differences between Eye – Head and Eye – Impact across subjects for the forehand and

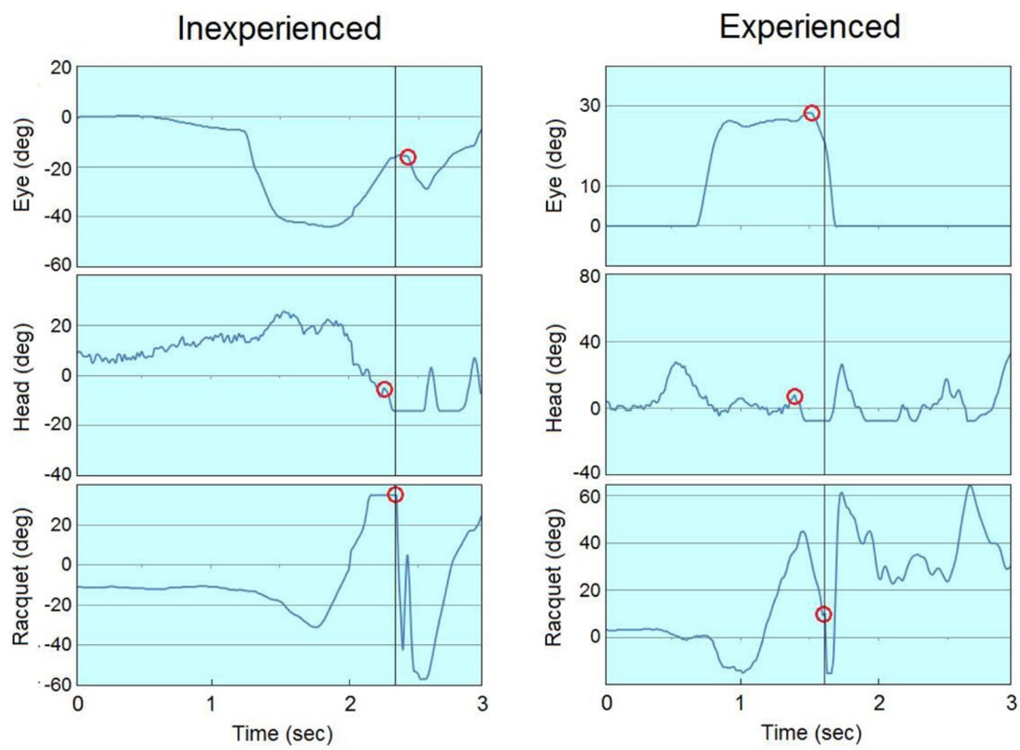

Figure 5: *Typical time traces of eye, head, and racquet motions for backhand showing similar effects as the forehand (Figure 4). Note that some traces were saturated because of the size of the movement, but these did not affect the data analysis. All movements were converted to degrees of angular rotation about their central axis of rotation. Subs IP2 and EP1.*

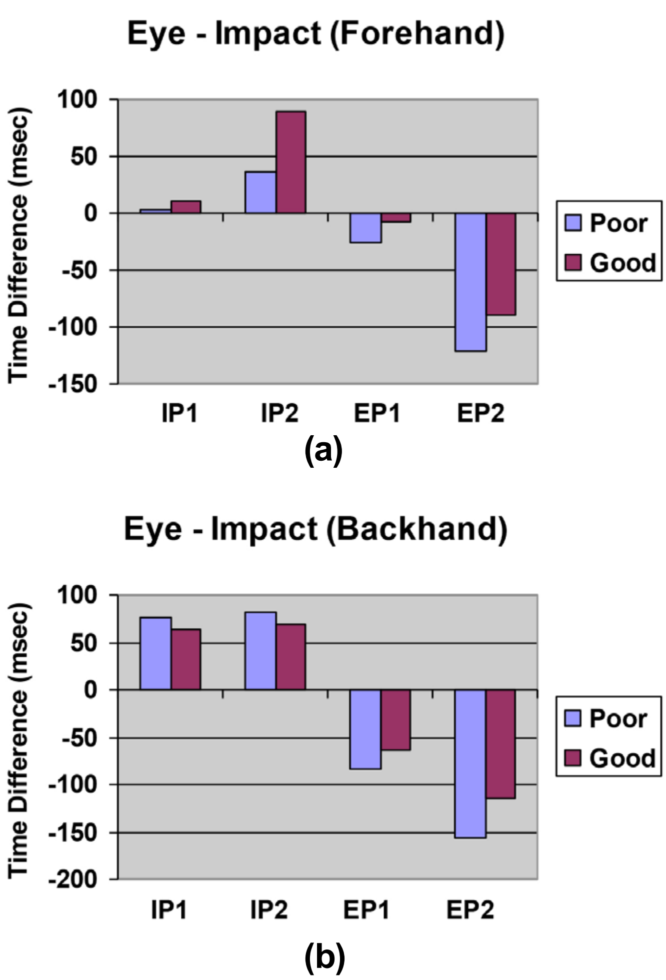

Figure 6: *Bar graph of time differences between eye and racquet impact (Eye–Impact) for both (a) forehand and (b) backhand for the inexperienced players (IP1 and IP2) and experienced players (EP1 and EP2).*

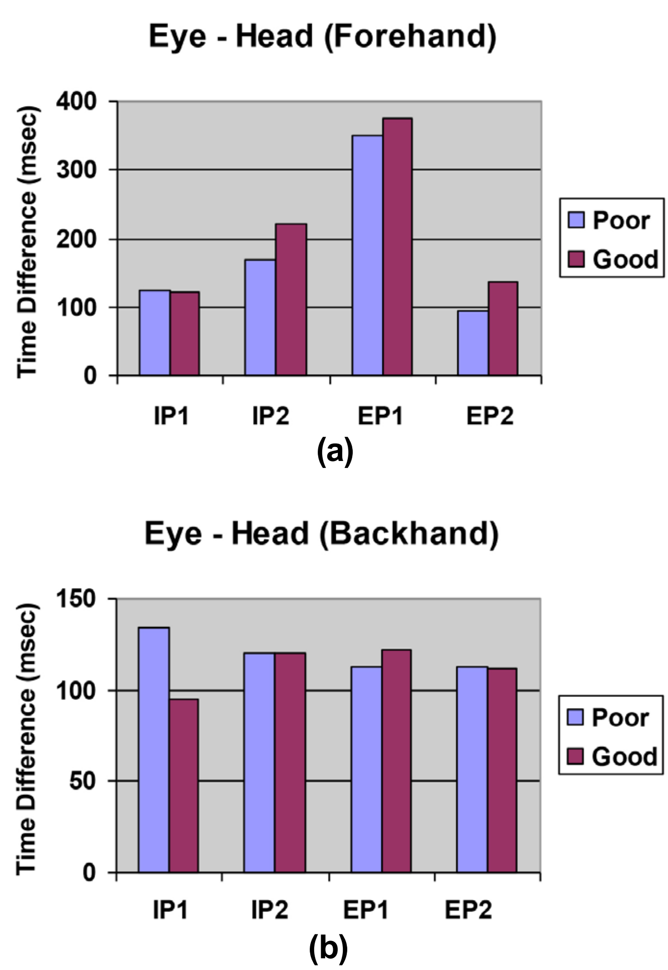

Figure 7: *Bar graph of time differences between eye and head (Eye–Head) movement initiation for both (a) forehand and (b) backhand for the inexperienced players (IP1 and IP2) and experienced players (EP1 and EP2).*

backhand strokes over the 4 sessions. The patterns of these differences can be more readily observed in the bar graphs for Eye – Impact (Figure 6a,b) and Eye – Head (Figure 7a,b) for both forehand and backhand for the inexperienced (IP) and experienced (EP) players. For both the forehand and backhand, eye movement initiation occurred after racquet impact for the inexperienced players (Figure 6a), but before impact for the experienced players (Figure 6b). In contrast, initiation of head motion occurred before both eye movement and racquet impact for both categories of players (Figure 7a,b).

There are three sub-trends that can be observed. First, for the backhand Eye – Impact time differences (Figure 6b), the "good" shots were shown to be more near to simultaneous occurrence than the "poor" shots. Second, the forehand Eye – Head time differences (Figure 7a) were greater for the "good" shots than the "poor" shots for three of the subjects, while the remaining subject showed no difference. Lastly, the magnitude of the Eye – Impact time difference was greater for the backhand than for the forehand, with the exception of Eye – Impact forehand "good" shots for IP2 (Figure 6a,b).

Based on the scoring system used to quantify performance, it was found, as may be expected, that the experienced players had higher performance scores than the inexperienced players.

Discussion

To conceptualize and to assess the time course of events throughout the groundstroke, for the purpose of discussion, we have divided this section into two phases: the Acquisition Phase (AP), followed by the Strike Phase (SP).

A. Acquisition Phase (AP)

During the AP, the player's attention is directed towards the area where the racquet will strike the ball. Studies have demonstrated that this involves the learned development of an optimization strategy for directing the focus towards the region of interest.[12-13,17-19] For example, high definition, slow-motion video of the great tennis player Roger Federer showed that in contrast to beginning players who simply followed the ball, Federer fixated on the anticipated area where the impact would be and adjusted his form to optimize performance of the shot.[13] Similarly, Vickers and others[17-18] found that tennis players used strategically-directed final fixation on a specific location prior to shot initiation, called the Quiet Eye, to optimize the shot required under various competitive conditions. Moreover, Rodriguez et al.[12] found that skilled players demonstrated earlier onset of ball tracking than less-skilled players, thus indicating that both the speed and location of directed attention were used to provide optimal preparation for the tennis stroke. Lastly, Land and McLeod[19] found that good cricket batsmen exhibited a shorter latency than poor batsmen in the first saccade directed towards the predicted position of the bowled ball after the initial bounce.

In the present experiments, during the AP, the initial position of the drop in the tennis ball was the same for each subject. The anticipated area of the ball at impact, that is, where it returned to the original position following the ball bounce, was repeatable and consistent and provided a simple set-up for striking the ball. Thus, this precluded a need for expert knowledge of eye fixation during the AP, so the initial fixation on the position of the ball would be similar for both experienced and inexperienced players. This allowed for a direct comparison of the timing differences during the SP between experienced and inexperienced players.

B. Strike Phase (SP)

During the SP, the head, eye, and hand-controlled racquet executed a coordinated sequence of movements to strike the ball. It involved timing control that is based on such concepts as pre-programming of motor movements, generation of power in the stroke, and control of accuracy in hitting the target.[3,7,17,20-22] Pre-programming is the process of pre-setting neuro-motor commands for executing a biomechanical motion. Pre-programming in the tennis stroke occurs in part from the fact that vision is blurred during the ball strike.[22] This permits optimizing body and arm biomechanics with relatively little dependence on visual resolution and detail during the moment of impact.

Several studies on ocular-dependent performances in various sports have found evidence for differences in preprogrammed motor control between expert and novice players. It was generally found that more-skilled athletes focused on the desired target longer than less-skilled athletes.[7,17,20,22] This is consistent with the concept of an optimal visual planning strategy in target acquisition.

Examples of such a strategy are found in various sports.[3,7,17,20-23] For example, in tennis, the concept of maintaining steady eyes and head is instilled into beginner players. However, as the players gain more experience, they become aware of the true meaning of the exercise, which is to compel the players to watch the impact or contact of the ball on the racquet. Most of the time, however, as the ball nears the moment of impact, it is blurry due to the speed of its motion and thus cannot actually be resolved for details.[22]

In the present experiment, the SP is concerned with neuro-motor control for striking the tennis ball. It was found that in all subjects, head movement initiation occurred before both eye movement and the time of impact. This may be related to the greater torque generation of the body core, and in turn rotation of the head, in the experienced players. This suggests a key strategic advantage related to improved eye-hand coordination in sports.[3,24]

An important new finding from the present study was that during the SP, there was a difference in timing for Eye – Impact between experienced and inexperienced players. Eye movement initiation occurred before racquet impact for experienced players but after impact for inexperienced players. This suggests that experienced players, presumably through varying degrees of training, but without being consciously aware of their own eye motions, have developed visual strategies that enhance overall performance. This is consistent with the views of various tennis theorists and researchers.[1,5,17] That is, the player who identifies the ball at an earlier time and exhibits better visual tracking skills during the athletic motions is at a distinct advantage when compared to the player who lacks similar expertise. Moreover, as players immerse themselves in training and become accustomed to the movements of the game, the visual strategies essentially become pre-programmed. Indeed, the development of such pre-programmed motions can provide an increase in reflex speed and allow for easier adaptation to unanticipated situations.[25]

Future Studies

Calculations for the appropriate sample size were made using the MedCalc software program based on our present pilot-study results, using the criterion of Type I Error at 0.05 and Type 2 Error at 0.20. (1) For Eye – Impact time difference (for both forehand and backhand) between Inexperienced (~ +50 msec) and Experienced subjects (~ -50 msec), or 100 msec, and s.d. of ~ 30 msec, the required sample size was 2 Experienced and 2 Inexperienced subjects, or a total of 4 subjects. (2) For Eye – Head (for both Experienced and Inexperienced subjects), the time difference between Good and Poor shots of ~ 40 msec and s.d. of ~ 30 msec, the required sample size was 10 Experienced and 10 Inexperienced subjects, or a total of 20 subjects. Thus, for the general behavior described in this study, a total of 4 subjects was sufficient. For the finer distinction between good and poor shots, a total sample size of 20 subjects would be more appropriate.

While subjects used in the present pilot study provided a good mix of levels of experience, it would be important to expand it to increase substantially the number of subjects (e.g., 20 subjects) and perhaps to add another expertise level, namely professional tennis players. This would provide greater confidence regarding the generality and significance of our findings, as well as a better understanding of the biomechanical, pre-programmed neuro-motor, and strategic differences among the various levels of tennis players.

Conclusion

This pilot study was the first to examine quantitatively timing differences that distinguish between inexperienced and experienced players during the Strike Phase (SP) in tennis. The present findings indicate that both experienced and inexperienced players exhibit head movement initiation before both eye movement and racquet impact. This suggests a general neuro-motor strategy for racquet motions, whereby the head initiates the rotational motion of the body to provide power in the groundstroke. Moreover, the present findings revealed that, following head initiation, experienced players initiate eye fixation prior to racquet impact, whereas inexperienced players initiate eye fixation after racquet impact. This may reflect an optimal, pre-programmed strategy used by the experienced player that was learned through training and repeated practice (i.e., motor learning) to provide both greater accuracy and consistency in the groundstroke.

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