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ORIGINAL

A Comparison of Head-Hand Coordination Patterns during Squash Forehand Strokes in Expert and Less-Skilled Squash Players

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Objective: To compare head and hand movement patterns during squash forehand motions between experts and less-skilled squash players.

Method: Four experts and four less-skilled squash players participated in this study. They performed squash forehand swings and a VICON motion analysis system was used to obtain displacement and velocity data of the head and right hand during the movement. Mann-Whitney *U*-tests were performed to compare head and hand range of motion and peak velocity, and cross-correlation was performed to analyze the head-hand coordination pattern between groups in three movement directions.

Results: In terms of head and hand kinematic data, experts had greater head range of motion during down swings than less-skilled squash players. Experts seemed to reach peak hand velocity at impact by reaching peak head velocity followed by hand peak velocity within a given temporal sequence. In terms of head-hand coordination patterns, both groups revealed high positive correlations in the medial-lateral direction, indicating a dominant allocentric coordination pattern. However, experts had uncoupled coordination patterns in the vertical direction and less-skilled squash players had high positive correlations. These results indicate that the head-hand movement pattern likely an important factor squash forehand movement.

Conclusion: Analysis of head and hand movement patterns could be a key variable in squash training to reach expert-level performance.

Keywords: Allocentric, Head-hand coordination, Expert, Squash forehand stroke

INTRODUCTION

All human movements are produced by synergy among various body components and not by individual control of those components. Swinnen (2002) suggested that there are two elementary coordination rules on all such movements. The egocentric principle is explained by "in-phase" (Φ=0), when movements of homogeneous limbs (i.e.: left and right upper limb) involves movement of the muscles on the same side of the axis of symmetry, and "anti-phase" (Φ=180), when the movement involves different muscles on the parallel direction. On the other hand, the allocentric principle defines in-phase as the movement of inhomogeneous limbs (i.e.: an upper and lower limb) in the same direction and anti-phase as movement in opposite directions.

The experiment by Kelso (1984) using the forefingers on both hands, which represents the beginning of studies on motor coordination, was conducted as an effort to demonstrate the existence of such elementary coordination rules. The subjects were instructed to perform the task of moving the forefingers in opposite phase (i.e.: both fingers simultaneously moving to the left or right) but when they were instructed to gradually increase the speed of the finger movement, the direction of the movement changed to same phase (i.e.: both fingers moving inward or outward). In other words, as the speed of the movement increased, the movement changed to same phase, representing a more stable state. Based on these results, it is determined that movement of the same type of limbs are bound more strongly by same phase, which is the preferred behavior pattern based on the egocentric principle. Meanwhile, the coordination between the legs and arms follows the allocentric principle (Baldissera, Cavallari, & Civaschi, 1982; Swinnen, 2002). For example, in the study by Baldissera et al. (1982), movement of the arms and legs in the same direction showed stronger temporal and spatial coordination than movement in the opposite direction. In other words, movement between different types of limbs is based on the allocentric principle, showing a stronger synchronization tendency when different body parts simultaneously exhibit the same phase.

Such inter-limb coordination is controlled by elementary coordination rules, and this fact has been proven through numerous experiments (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Spencer & Ivry, 2007; Swinnen, Jardin, Meulenbroek, Dounskaia, & Den Brandt, 1997; Temprado, Swinnen, Carson, Tourment, & Lauren, 2003). However, most studies were limited to simple motions in attempts to explain the elementary coordination rules of human movement generation. In this case, what would be the coordination type preferred by experts with much practice compared

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to less-skilled players with little practice? Do the elementary coordination rules exist in these practiced motions? To answer these questions, it is necessary to select tasks involving complex motions in sports settings to examine the principle behind skilled motions.

The method most often used to explain the principle behind skilled motions in various sports is the comparison of experts to less-skilled players (Kim, 2007). In actual sports events, expert and less-skilled players show appreciable qualitative differences in form (Roh & Park, 2013), which appear in a variety of ways depending on the task performed. In racquet sports, a swing task represents a complex motion that requires synchronous spatial coordination between body components and timing to accurately hit a ball in flight, which can be acquired as a skill by practicing over a long period of time.

To date, studies using the expert-less-skilled research paradigm in racquet sports to explain the movement characteristics of experts have focused mostly on the characteristics of the upper limbs holding the racquet (Elliott, Marshall, & Noffal, 1996; Jo, Yoo, & Yoon, 2013; Kim & Kim 2010; Oh, Choi, & Nam, 2006). In studies on tennis (Oh et al., 2006), squash (Elliott et al., 1996; Roh & Park, 2013), and badminton (Jo et al., 2013), the results showed that for accurately striking the ball, expert players have excellent ability to effectively control the movement of their hand, which represents the distal segment of the upper limb. However, there are limitations in using only kinematic data from studies on the movement of an upper limb within the same type of limbs to clearly explain the coordination principle behind swing motions that require interactions between various body components.

Unlike existing studies, a recent study by Lafont (2007, 2008) focused on top tennis players using photo analysis. The results showed that expert players exhibited a pattern of having their head orientation already fixed in the contact zone where impact with the ball takes place, and this unique movement was maintained until completing the swing. Therefore, head movement in experts that allow them to stably fix the direction of their eyes and head at the point of impact in advance can be considered as a major factor for successfully performing swing tasks. Previously, Ripoll and Fleurance (1988) also examined the characteristics of eye and head movement during forehand strokes in table tennis. The results showed that it was very important for the players to fix the direction of their eyes and head orientation to the point of impact in advance to accurately and quickly predict where the ball will bounce. However, because the study of Lafont (2007, 2008) was a qualitative study using photo analysis, there are limitations with respect to the research methodology, whereas the study by Ripoll and Fleurance (1988) was limited in explaining the coordination between head movement and swing motion since it did not analyze actual swing motions. Based on these results, it is believed that the characteristics of the head movements of expert players during swing motions in racquet sports may contribute to successful performance. To prove this, it is necessary to conduct comparative analyses using quantitative research methodologies in both experts and less-skilled players and to expand the research to include various swing motions. Accordingly, studies that identify differences in skill levels based on head movement during swing motions and coordination between swing motions can provide important information for effectively acquiring sports skills.

Squash has become a popular sport among female college students (Yoon, 2011). Squash has been not only positioned as a lifestyle sport but it was also selected as an official event in the 2004 Korean National Sport Festival, resulting in much effort being put into developing top class players. As a result of such efforts, bronze medals were won in the women's team event during the 2002 Busan Asian Games and 2014 Incheon Asian Games. However, academic research trends show that studies on squash events are still lacking (Lee & Shin, 2014). Moreover, most of the studies to date have examined the kinematic characteristics of swing motions performed by male athletes (An, Ryu, Ryu, So, & Lim, 2007; Cho & Kim, 2007; Elliott et al., 1996; Kim & Park, 2008; Lee & Lee, 2007), whereas quantified data on swing characteristics in female athletes are limited. Accordingly, the present study selected expert female athletes as the participants.

The objective of the present study was to conduct a comparative analysis of the coordination between head and hand movements, representing movement between different types of limbs, by applying an expert-less-skilled research paradigm for the basic motion in squash - the forehand stroke. In addition, the study aimed to investigate whether the elementary coordination rules suggested by Swinnen (2002) apply in skilled motions and not just simple motions used in existing studies and to identify the optimal form of coordination for the squash forehand swing in expert players.

METHODS

1. Participants

The participants of this study were four experts and four less-skilled players. The expert group (mean age: 24.5 ± 2.4 years, height: 167.8 ± 1.7 cm, weight: 58.5 ± 1.3 kg) included elite athletes with over 10 years of experience and top-three finishes in national tournaments. The less-skilled group (mean age: 23.8 ± 1.0 years, height: 162.8 ± 1.0 cm, weight: 55.5 ± 1.7 kg) included women who learned squash by regularly participating in two weekly sessions for 6 months at the community sports center at "E" University. The participants all voluntarily consented to participate in the study.

2. Apparatus and task

The experiment was conducted in the 3D motion analysis laboratory at "E" University. The task was the squash forehand stroke motion. To capture squash forehand stroke motions, nine MX13 cameras (VICON MX, Oxford, UK) and analytic software (Nexus, Polygon) were used. This experimental task is the method most often used by coaches when teaching squash. The research assistant drops the ball above the racquet placed on the ground and the participant hits the ball using a forehand swing. To ensure that the same task was performed by each participant, the ball was dropped consistently from a height of 1 m and the participants were instructed to hit the center of a round target placed on a wall 5 m in front. All participants used the same "H" brand racquet, and considering the laboratory conditions, the bounciest ball with a blue point was used.

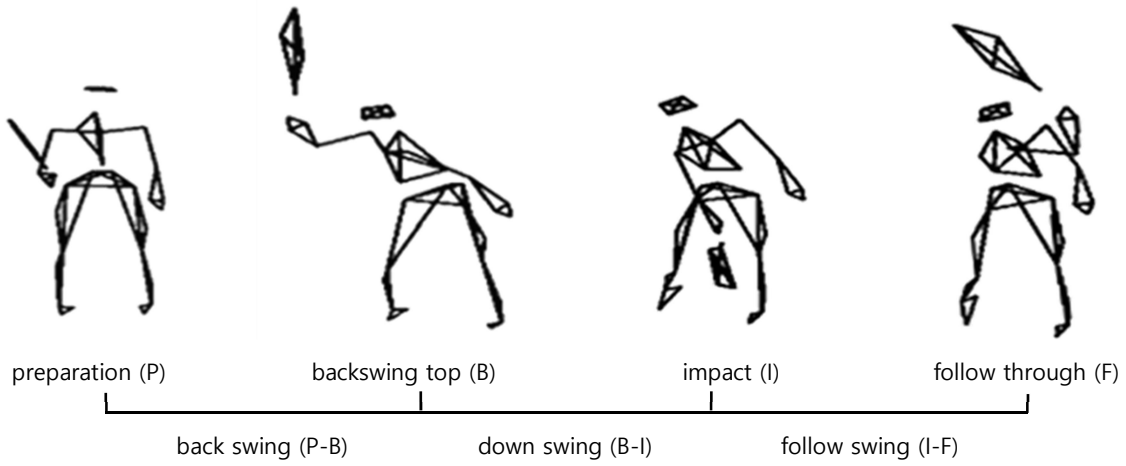

Figure 1. Four events (P, B, I, F) and three phases (backswing, downswing, follow-swing)

3. Procedure

Prior to the experiment, the researcher personally met the squash coach in charge. After explaining the objective of the study, consent was obtained and the study population was selected from those who would voluntarily consent to participate. When each candidate arrived at the laboratory, sufficient explanation was given on the objectives and procedures of the study, after which written consent was obtained. The participants each wore a black sleeveless shirt and black tights. After completing the physical measurements needed for the analysis, a total of 44 reflective markers were attached, five on the racquet and 39 on body joint points, using the Plug-in-gait model. After completing all preparations for the experiment, the participants were given 5 min of stretching time and swing practice, after which each participant performed 10 forehand stroke motions. Among the 10 forehand stroke motions performed, three motions that resulted in an accurate hit on the round target were selected by an expert panel (two squash coaches and one professor of physical education) and used in the analysis.

4. Data analysis

The present study used a forehand stroke task, the most basic motion in squash, to investigate the differences in coordination between distal segment movements involving the head and arm according to skill levels. Each squash forehand stroke motion was divided into three phases: backswing (from the ready position to the top of the backswing), downswing (from the top of the backswing to impact), and follow-swing (from impact to follow-through) (Figure 1). The dependent variables were displacement and velocity with respect to head and hand movements involved in squash forehand stroke motion. To obtain kinematic data, a VICON motion analysis system was used to acquire images from nine cameras at a rate of 120 fps. The data of spatial coordinates from the markers attached to the right wrist holding the racquet and the forehead were processed by smoothing at a cut-off frequency of 10 Hz using a Butterworth low-pass filter in the Nexus software program to derive the head and hand displacement and velocity data. The data derived in this manner were normalized with a time axis of 100% using Polygon software for comparisons between the two groups.

The three-axis displacement data (medio-lateral = ML, antero-posterior = AP, vertical = V) were defined so that ML axis would represent the direction of ball movement (left = +, right = -), AP axis would represent the anterior and posterior movement of the ball (posterior = +, anterior = -), and V axis would represent the vertical movement of the ball (up = +, down = -).

The major dependent variables were the maximum range of motion (ROM) and peak velocity of head and hand displacement. For statistical processing, the Shapiro-Wilk test was performed on the dependent variables to test for normality. Since the normal distribution could not be assumed, nonparametric statistical methods were used. The differences in the kinematic variables for head and hand movements between the two groups were analyzed using the Mann-Whitney *U*-test. In addition, correlation analysis was performed to determine the correlations between head and hand movements. The statistical significance level for all analyses was $p<.05$ and SPSS 21.0 (SPSS Inc, USA) was used for all analyses.

RESULTS

1. Swing duration

The total duration of the forehand swing was shorter in the expert group (1.38 ± 0.08 sec) than in the less-skilled group (1.65 ± 0.12 sec). When the forehand swing was divided into three phases (backswing, downswing, and follow-swing) and the duration of each phase was converted to a percentage, the expert group (20.25 ± 5.91%) had a statistically significantly shorter downswing duration than the less-skilled group (23.67 ± 4.22%) ($U=36.000$, $p=.036$). Significant differences between the two groups were not found for the backswing and follow-swing phases (backswing: $U=49.000$, $p=.190$; follow-swing: $U=70.500$, $p=.944$) (Figure 2).

2. Head kinematics

To compare the characteristics of head movement during forehand swing motions between the expert and less-skilled groups, the maximum ROM and peak velocity of head displacement were examined. For ROM of head displacement, differences in height between the members of the two groups were considered, where the start of displacement to the ML axis indicated the maximum range while moving further from the direction of the ball, the AP axis indicated the maximum range while moving closer to the direction of the ball in the antero-posterior direction, and the V axis indicated the maximum range while moving closer to the direction of the ball in the vertical direction. All values were converted to positive (+) values. Moreover, instead of simply comparing the two groups at one specific point (e.g.: top of the backswing), we divided the forehand stroke motion into three phases of backswing (P-B), downswing (B-I), and follow-swing (I-F) to analyze changes in the pattern of head movement over time (Figure 3).

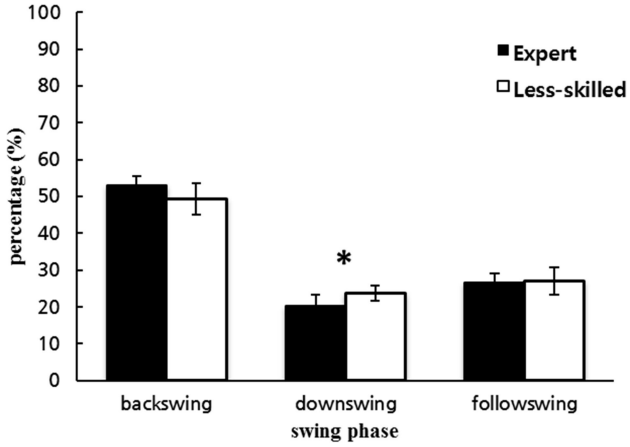

Figure 2. Swing phase duration in expert and less-skilled squash players

1) Head range of motion

The Mann-Whitney *U*-test was conducted to investigate the differences in ROM of head displacement according to skill levels. The results showed that the expert group had statistically significantly greater ROM than the less-skilled group in all three directions (ML: $U=22.500$, $p=.003$, AP: $U=21.000$, $p=.002$, V: $U=12.000$, $p=.000$) (Table 1). In other words, during the downswing, the ROM of head displacement in the expert group became further from the direction of the ball in the ML axis, closer in the AP axis, and closer in the V axis than in the less-skilled group (Figure 3).

Table 1. Comparisons of head range of motion between expert and less-skilled players (unit: mm)

Axis	Group	Head range of motion					
		Mean (SD)	Average rank	*U*	Z	*p*	*d*
ML	Expert	107.42 (47.13)	16.63	22.500	-2.859**	.003	0.36
	Less-skilled	52.50 (23.53)	8.38				
AP	Expert	659.16 (91.01)	16.75	21.000	-2.945**	.002	0.38
	Less-skilled	533.33 (88.18)	8.25				
V	Expert	216.08 (51.17)	17.50	12.000	-3.464**	.000	0.52
	Less-skilled	101.58 (58.79)	7.50				

Note. significant at *$p<.05$, **$p<.01$. ML = medio-lateral; AP = antero-posterior; V vertical

Table 2. Comparisons of head peak velocity between expert and less-skilled players (unit: mm/s)

Axis	Group	Head peak velocity					
		Mean (SD)	Average rank	*U*	Z	*p*	*d*
ML	Expert	518.17 (131.91)	11.08	55.000	-0.982	.340	0.04
	Less-skilled	549.75 (110.37)	13.92				
AP	Expert	1045.91 (142.98)	13.58	59.000	-0.751	.478	0.03
	Less-skilled	1009.33 (181.78)	11.42				
V	Expert	652.58 (124.73)	13.67	58.000	-0.808	.443	0.03
	Less-skilled	610.50 (215.90)	11.33				

Note. significant at *$p<.05$, **$p<.01$. ML = medio-lateral; AP = antero-posterior; V vertical

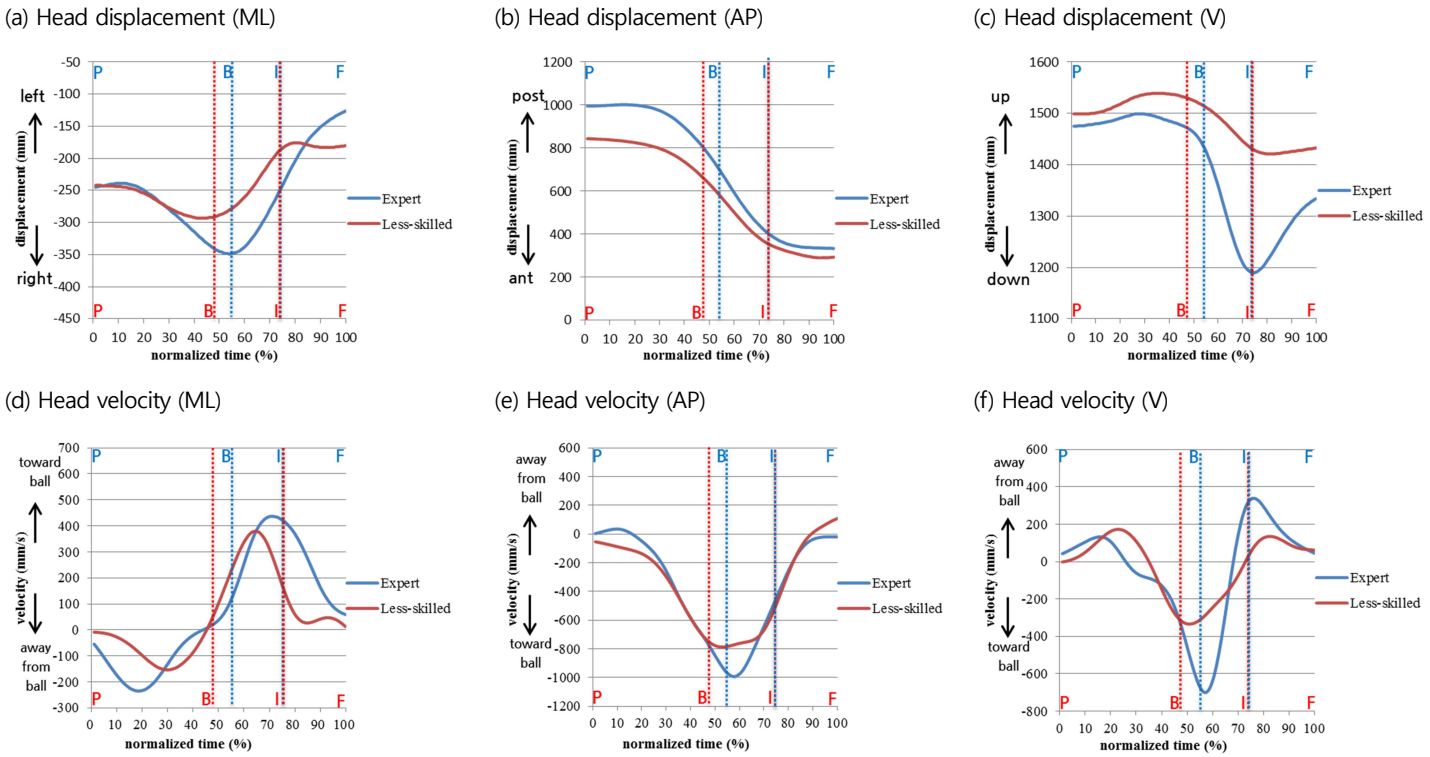

Figure 3. Representative head displacement (up) and velocity (down) profiles of an expert squash player (blue color) and a less-skilled squash player (red color) are shown in the medial-lateral (ML), anterior-posterior (AP), and vertical (V) axes. The vertical dot bars indicate preparation (P), backswing top (B), impact (I), and follow-through (F) in order during a squash forehand swing.

Table 3. Comparisons of hand range of motion between expert and less-skilled players (unit: mm)

Axis	Group	Hand range of motion					
		Mean (SD)	Average rank	*U*	Z	*p*	*d*
ML	Expert	324.58 (70.75)	14.00	54.000	-1.039	.319	0.05
	Less-skilled	273.75 (48.39)	11.00				
AP	Expert	706.21 (56.18)	14.50	48.000	-1.386	.178	0.08
	Less-skilled	668.90 (63.68)	10.50				
V	Expert	375.16 (94.01)	15.83	32.000	-2.309*	.020	0.23
	Less-skilled	249.42 (128.09)	9.17				

Note. significant at *p<.05, **p<.01. ML = medio-lateral; AP = antero-posterior; V vertical

2) Head peak velocity

A Mann-Whitney *U*-test was conducted to investigate the differences in peak velocity of head displacement according to skill levels. The result showed no statistically significant differences between the two groups (ML: U=55.000, p=.340, AP: U=59.000, p=.478, V: U=58.000, p=.443) (Table 2). Interestingly, peak velocity of head movement showed large differences between the two groups at different time points (Figure 3d). The expert group showed an increase in velocity of head movement in the direction of the ball and reached the peak velocity immediately before impact, whereas the less-skilled group showed acceleration up to the initial downswing followed by deceleration as impact was made with the ball (Figure 3).

3. Hand kinematics

1) Hand range of motion

A Mann-Whitney *U*-test was conducted to investigate the differences in the ROM of hand movement according to skill levels. The results showed that the expert group (375.16 ± 94.01 mm) had statistically significantly greater ROM than the less-skilled group (249.42 ± 128.09

mm) in the V axis (U=32.000, p=.020). However, there were no statistically significant differences between the two groups in the ML and AP axes (ML: U=54.000, p=.319, AP: U=48.000, p=.178) (Table 3). As shown in Figure 4-c, the expert group made impact with the ball at a lower position on the V axis than the less-skilled group (Figure 4).

2) Hand peak velocity

A Mann-Whitney U-test was conducted to investigate the differences in the peak velocity of hand movement according to skill levels. The results showed a statistically significant difference between the two groups in the V axis (U=0.000, p=.000). However, there were no statistically significant differences between the two groups for the ML and AP axes (ML: U=44.000, p=.114, AP: U=51.000, p=.242) (Table 4). Interestingly, in the expert group, hand velocity was higher than in the less-skilled group in all directions, with velocity peaking immediately before impact and decreasing at impact (Figure 4).

4. Head-hand coordination

Correlation analysis was conducted to investigate the coordination between the displacement of the head and hand during forehand

Table 4. Comparisons of hand peak velocity between expert and less-skilled players (unit: mm/s)

Axis	Group	Hand range of motion					
		Mean (SD)	Average rank	U	Z	p	d
ML	Expert	6,908.50 (564.41)	10.17	44.000	-1.617	.114	0.11
	Less-skilled	7,404.83 (775.59)	14.83				
AP	Expert	5,116.16 (435.46)	10.75	51.000	-1.212	.242	0.06
	Less-skilled	5,366.91 (745.41)	14.25				
V	Expert	5,963.16 (546.38)	18.50	0.000	-4.157**	.000	0.75
	Less-skilled	4,001.25 (633.46)	6.50				

Note. significant at *p<.05, **p<.01. ML = medio-lateral; AP = anterior-posterior; V = vertical

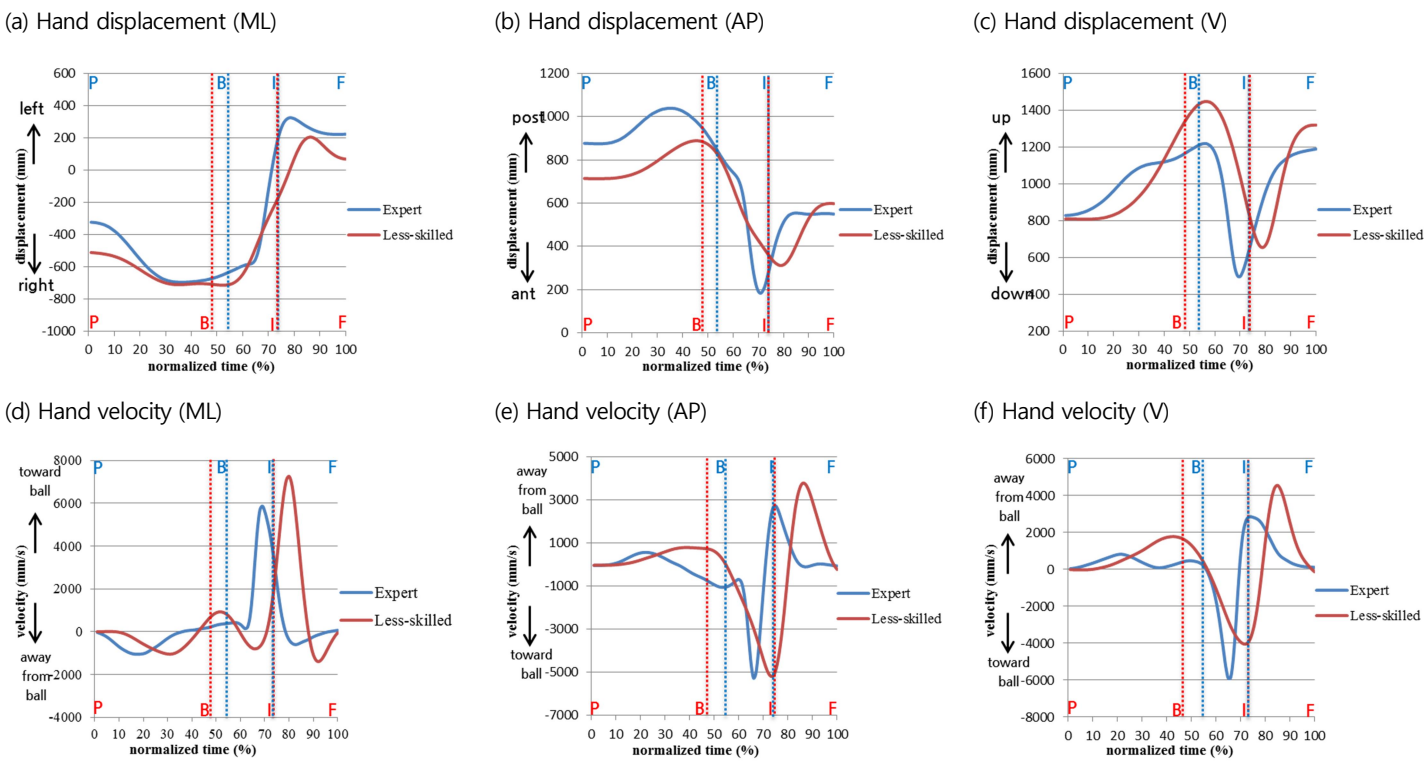

Figure 4. Representative hand displacement (up) and velocity (down) profiles of an expert squash player (blue color) and a less-skilled squash player (red color) are shown for the medial-lateral (ML), anterior-posterior (AP), vertical (V) axes. Vertical dot bars indicate preparation (P), backswing top (B), impact (I), and follow-through (F) in order during squash forehand swing.

Table 5. Correlations of head-hand displacement and velocity between expert and less-skilled players

	Displacement			Velocity		
	ML	AP	V	ML	AP	V
Expert	.952**	.851**	.160	.717**	.515**	.594**
Less-skilled	.910**	.760**	.246*	.501**	.687**	.729**

Note. significant at *$p<.05$, **$p<.01$

swings according to skill level. The two groups showed highly positive correlations in the ML and AP axes (expert: $r=.952$ in ML, $r=.851$ in AP; less-skilled: $r=.910$ in ML, $r=.760$ in AP). Meanwhile, the two groups showed differences in the V axis. The less-skilled group showed statistically significant positive correlations ($r=.246$, $p<.05$), whereas the expert group did not ($r=.160$, $p>.05$). Correlation analysis was conducted to investigate the coordination between the velocities of the head and hand during forehand swings according to skill levels. The two groups showed statistically significant positive correlations in all three axes (expert: $r=.717$ in ML, $r=.515$ in AP, $r=.594$ in V; less-skilled: $r=.501$ in ML, $r=.687$ in AP, $r=.729$ in V). The highest positive correlation was found in the ML axis ($r=.717$) in the expert group and V axis ($r=.729$) in the less-skilled group (Table 5).

DISCUSSION

Swinnen (2002) suggested that two elementary coordination rules underlie the basis of numerous human movements. Based on such rules, skilled motions can be generated through practice and experience. If this hypothesis is true, what would be the difference between expert squash players with significant practice and less-skilled players with little practice? With this in mind, the present study had two major objectives. The first was to conduct a comparative analysis of head and hand movements during squash forehand stroke motions by applying an expert-less-skilled research paradigm. The second was to investigate whether the elementary coordination rules suggested by Swinnen (2002) apply in learned skill motions and to identify the optimal form of coordination for the squash forehand swing in expert players. To achieve these objectives, we examined the changes in the patterns of individual movements with variables of the displacement of the head and hand as well as the velocity that appear during the squash forehand swing and investigated the correlations between the variables for head and hand coordination.

Kinematic analysis of head and hand movements according to skill levels showed that there were no major differences in hand movements during forehand swings but contrasting results for head movement. In other words, both groups showed similar hand movements during forehand swings but the expert group showed greater head range of motion than the less-skilled group in all three axes. Previous studies on the relationship between head movement and club head speed in golf swings reported similar results (Hong, Park, & Park, 2008). In these previous studies, professional golfers had greater head movement during their swing than amateur golfers, which was explained as a strategy for increasing the club head speed at impact. Since the present study did not directly measure racquet head speed, there are limitations in making a direct comparison. However, the expert group had lower hand velocity at the point of impact than the less-skilled group, which contradicted the findings in previous studies (expert = 5,978.9 ± 1,880.43 mm/s, less-skilled = 7,279.50 ± 772.34 mm/s at impact in ML) ($p<0.05$). These differences may be attributable to the studies having different objectives. The participants in the present study performed the task of striking the ball to accurately hit the center of a given target. In other words, different tasks involving striking a ball hard versus accurately show differences in the velocity of the hand holding the racquet at the point of impact. Meanwhile, greater head range of motion when performing the swing task was a common characteristic found among experts, regardless of the study objective.

Moreover, there were significant differences between the groups with respect to not only head displacement but the ability to control the velocity of head movement. Specifically, there were no statistically significant differences between the groups with respect to head movement in all three axes. However, there were statistically significant differences between the two groups regarding when the peak velocity was generated. In other words, the expert group reached peak velocity for both the head and hand immediately before impact, followed by a decrease in velocity at impact. In contrast, the less-skilled group tended to impact the ball after reaching peak head velocity immediately after the top of the backswing (Figure 3-d). The expert group made impact by creating a whipping motion with the head in the direction opposite to ball movement to decrease the velocity of head movement in the direction of ball movement. Previous studies on various racquet sports identified an order of coordination starting from the proximal segments in the arm holding the racquet during forehand swings and ending in the distal segments. However, these studies could not identify the coordinated motion between different types of limbs (i.e.: head and arm) (Lafont, 2008; Lee & Lee, 2007; Ripoll & Fleurance, 1988; Roh & Park, 2013). In this context, the significance of the present study was that it confirmed the temporal constraints that appeared in head and hand movements of the present study to be an essential element in the process of acquiring the necessary skill for performing an effective swing.

Analysis of the coordination of the head and hand according to skill levels based on the elementary coordination rules by Swinnen (2002) showed that the less-skilled group exhibited static coordination, with the head and hands moving in the same direction along all three axes. In other words, the less-skilled group were strongly confined to the same phase, representing a stable coordination pattern preferred by the allocentric principle. Such results were consistent with the findings by Lee, Ishikura, Kegel, Gonzalez, and Passmore (2008), who found that less-skilled golfers showed a pattern characterized by the head and putter moving in the same direction during putting. Therefore, the swing motion of less-skilleds with little practice is generated and controlled in compliance with the elementary coordination rules. However, the expert group showed static coordination, with the head and hands moving in the same direction as ball movement, whereas in the vertical direction they showed non-constrained coordination, with the head

remaining steady while the hand was lifted during the backswing motion. The objective of the squash forehand swing motion is to relay the momentum generated by the coordinated movement of various body segments to the front, which is the desired direction of ball travel (Lee & Lee, 2007). To achieve this objective, the expert group used a strategy of facilitating head movement in the direction of the ball and making impact while suppressing head movement according to hand movement. The head and hand coordination of experts in this study can be explained by the results of the study by Zanone and Kelso (1992), which reported that the process of changing coordination from motor learning aspects represents a process of deviating from intrinsic coordination, losing the stability gained through practice, and transitioning to a new pattern of coordination suitable for the given task. In summarizing the results given above, there were differences in head and hand coordination between experts and less-skilleds according to the directionality of the motion generated during the swing. Even in such a complex swing task, differences according to skill levels could be proven through the allocentric principle suggested by Swinnen (2002).

Finally, an interesting finding was that differences in head and hand coordination between the two groups appeared in the direction of ball travel, with head displacement in the expert group behind the point of impact and the opposite being true in the less-skilled group (expert = -260.92 mm, less-skilled = -174.29 mm). This was similar to the results of the study by Ripoll and Fleurance (1988), which reported that for the forehand stroke in table tennis, expert players positioned their head at the point of impact in advance in order to hit the ball with exact timing. Meanwhile, the present study was able to quantitatively analyze the coordination between head movement and swing motion, which could not be quantified in previous studies (Lafont, 2007, 2008; Ripoll & Fleurance, 1988). A study by Vickers (1992) reported that with respect to the association between glance behavior and putter movement during golf putting, experts fixed their head movement for a longer period prior to impact to focus their view on the ball, which was partially consistent with the findings of the present study. The present study did not actually measure eye movement. However, head movement in the expert group, in which the head orientation, including eye movement, was positioned in advance at the point of contact and stably fixed, could be considered as a major factor for successfully performing the swing task.

CONCLUSION

The present study examined the individual kinematic movements of the head and hand according to skill levels and examined the association between the two variables. The results showed that head movement was different between skill levels during the backswing and downswing for generating effective impact. In other words, when striking the ball, the pattern of head movement in the expert group to control the exact timing of impact and sequential movement of the upper limb segments was an unavoidable characteristic developed with increased skill. Moreover, in keeping with the allocentric principle suggested by Swinnen (2002), the less-skilled group had head and hand movements confined to same phase in all three axes, which is the preferred behavior pattern. On the other hand, in the expert group, head and hand coordination in the direction of ball travel was more strongly constrained; the head and hands moved in the same direction as movement, whereas non-constrained coordination was shown in the vertical direction of ball movement. Accordingly, the present study demonstrated the existence of the elementary coordination rules suggested by Swinnen (2002) in complex skilled sports motion. Moreover, we conducted quantitative analysis to determine the differences in head and hand coordination and individual kinematic movements of the head and hand according to skill levels with the aim of identifying the optimal coordination pattern for the squash forehand swing in the expert group. The findings concerning the characteristics of head and hand coordination according to skill levels can provide basic data for effective skill learning for use by coaches in the context of on-field learning. The present study had a small study population size due to the limited number of female squash players. Therefore, future studies should recruit more candidates by broadening the scope of expert players so that the findings can be generalized. Moreover, future studies should directly measure changes in glance behavior according to ball movement during swing tasks to provide a clearer understanding of the characteristics of head movement in expert players.

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