Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

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To cite this article: Benjamin K. Williams, Ross H. Sanders, Joong Hyun Ryu, Philip Graham-Smith & Peter J. Sinclair (2020) The kinematic differences between skill levels in the squash forehand drive, volley and drop strokes, Journal of Sports Sciences, 38:13, 1550-1559, DOI: 10.1080/02640414.2020.1747828

To link to this article: https://doi.org/10.1080/02640414.2020.1747828

Published online: 15 Apr 2020.

JOURNAL OF SPORTS SCIENCES
2020, VOL. 38, NO. 13, 1550–1559
https://doi.org/10.1080/02640414.2020.1747828

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The kinematic differences between skill levels in the squash forehand drive, volley and drop strokes

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ABSTRACT

Knowledge of the kinematic differences that separate highly skilled and less-skilled squash players could assist the progression of talent development. This study compared trunk, upper-limb and racket kinematics between two groups of nine highly skilled and less-skilled male athletes for forehand drive, volley and drop strokes. A 15-camera motion analysis system recorded three-dimensional trajectories, with five shots analysed per participant per stroke. The highly skilled group had significantly ($p < 0.05$) larger forearm pronation/supination range-of-motion and wrist extension angles at impact than the less-skilled. The less-skilled group had a significantly more "open" racket face and slower racket velocities at impact than the highly skilled. Rates of shoulder internal rotation, forearm pronation, elbow extension and wrist flexion at impact were greater in the drive stroke than in the other strokes. The position of the racket at impact in the volley was significantly more anterior to the shoulder than in the other strokes, with a smaller trunk rotation angular velocity. Players used less shoulder internal/external rotation, forearm pronation/supination, elbow and wrist flexion/extension ranges-of-motions and angular velocities at impact in the drop stroke than in the other strokes. These findings provide useful insights into the technical differences that separate highly skilled from less-skilled players and provide a kinematic distinction between stroke types.

ARTICLE HISTORY
Accepted 13 March 2020

KEYWORDS
Swing mechanics; accuracy; racquet; elite athlete

Introduction

The fundamental skill in the game of squash is the ability to hit the ball successfully within the area of play. Considering the location of the ball relative to the court, location of the opponent, the tactics currently being employed, and the skill level of the player, a number of different types of squash strokes can be used to hit the ball. The most prevalent squash strokes utilised during match play are drives, volleys and drop shots (Vučković et al., 2013). All these strokes can be played as either a forehand or backhand stroke and thus require a different technique to hit the ball successfully. The ability to hit the ball successfully using different strokes is an important skill that is developed over time and may distinguish players of different skill levels (Ariff et al., 2012; Landlinger et al., 2010a).

Some of the key factors determining the speed, trajectory and success of a hit ball (excluding racket technology) are racket speed, racket face trajectory and the orientation angle of the racket face at impact (Elliott et al., 1997). These critical factors can be controlled and modified by movements of the trunk, lower and upper-limbs. The linear and angular movements of the trunk and upper-limb segments have been shown to play an important role in effective stroke production (Elliott et al., 1997; Woo, 1993). Consequently, the kinematics of the trunk and upper-limb segments have been the focus of numerous research studies across several racket sports and have provided valuable information to increase the understanding of stroke production (Elliott et al., 1989, 1996; Landlinger et al., 2010b).

There have been two kinetic chain models proposed for tennis stroke production, a "power stroke" and a "precision stroke" segment coordination strategy (Elliott, 2006). Elliott (2006) suggested that in the power stroke method the movement of the individual body segments must be coordinated to produce maximum racket velocity, whereas in the precision stroke the body segments work more as a single unit, with reduced contributions from the upper-limb segments. In squash, Elliott et al. (1996) assessed the contributions of trunk and upper-limb segment rotations in the development of racket head velocity during the forehand drive. It was shown that internal rotation of the upper-arm, hand flexion and forearm pronation made the strongest contribution to mean forward racket velocity at impact, advocating the squash drive as a power stroke.

Research on the kinematics of squash strokes has thus far, with the exception of two conference abstracts (Ariff et al., 2012; Kim et al., 2018), focused predominantly on the techniques used to generate racket head speed (Chapman, 1986; Elliott et al., 1996; Woo & Chapman, 1992). Furthermore, these studies have tended to analyse elite or highly skilled players exclusively, resulting in an absence of valuable information available on the variation in the stroke mechanics between players of differing skill levels. In other racket sports such as tennis, table tennis and badminton there have been numerous studies showing kinematic differences between players of different skill levels (tennis: Landlinger et al. (2012, 2010a, 2010b), Rogowski et al. (2007), and Whiteside et al. (2013a, 2015), table

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tennis: Iino and Kojima (2009, 2011), badminton: Sørensen et al. (2011)). These types of analyses provide valuable objective data that can help guide skill development programmes (Whiteside et al., 2013a).

In pursuit of sporting excellence, athletes may advance through various talent development phases that can include sport-specific skill development and refinement (Gulbin et al., 2013). Squash skill development requires knowledge of the swing kinematics that constitute an efficient, successful technique (Ariff et al., 2012; Lees, 2003). As such, comparing the kinematics of the most common squash strokes, across player skill levels, would provide useful insights into the distinction between highly skilled and less-skilled players and how the performance of less-skilled players may be improved. Therefore, this study aims to compare the trunk, dominant upper-limb and racket kinematics of highly skilled and less-skilled squash players in the forehand drive, volley and drop strokes, as well as identify any differences between strokes.

Methods

Participants

Eighteen male squash players volunteered to participate in the study. All participants were members of a national sports academy that included players in the 'under 15', 'under 17', 'under 19' and "open" age categories. All players under the age of 19 were ranked in the top 5 in their nation for their respective age groups, while all open players had played professionally for at least 2 years. For the purpose of analysis, participants were allocated into two groups; highly skilled (n = 9, age 22.7 ± 6.6 years, height 1.76 ± 0.07 m, weight 69.9 ± 10.2 kg) and less-skilled (n = 9, age 14.7 ± 1.7 years, height 1.68 ± 0.08 m, weight 60.5 ± 11.0 kg). Group allocation was determined objectively, with participants ranked on a squash accuracy test and then divided into two groups using a score of 60% to separate the highly skilled from the less-skilled. The accuracy test used for group allocation was the "Hunt Squash Accuracy Test" (HSAT) which has been previously validated against match performance (Williams et al., 2018). Mean HSAT group scores were 73 ± 7% and 51 ± 6% for the highly skilled and less-skilled groups, respectively. Group allocation was affirmed by three expert coach opinions whereby the coaches independently divided participants into two skill groups based on stroke technique. The results of both group assignment methods were in agreement. All participants were free from injury at the time of testing and reported no limitations or discomfort throughout the tests. Two participants were left-handed, the other 16 were right-handed. All participants gave written informed consent before participating in the study, which was approved by the ADLQ Institutional Review Board (E2017000216).

Equipment setup and testing protocol

All testing took place at an indoor squash training facility on a four-sided glass squash court (ASB ShowGlassCourt, Czech Republic). Three-dimensional motion analysis data were collected using a 15-camera optical motion capture system operating at 200 Hz (Vicon Motion Systems, UK). The 15 cameras were positioned around each of the four glass walls of the court such that a capture volume of approximately 6 m x 6 m was established around the centre "T" area of the court (Figure 1). A global coordinate system was defined as per Figure 1.

In order to check the validity of the motion analysis system to accurately collect data through the glass walls of the squash court, a calibration check was performed. Data were collected on a rigid object (wand) with 5 fixed markers (14 mm diameter) of known coordinates and distances. The wand was moved around the calibrated volume and swung with speed similar to that of a squash shot for approximately 10 s. The mean distance between markers as well as the average angle formed between lines joining the markers was calculated and compared to the known values. The mean absolute error for length and angle were 0.3 mm and 0.1°, respectively.

Each participant performed a self-selected pre-game warm-up, which included warming the ball, prior to the start of the data collection. The ball was kept in a state of "match readiness" throughout the data collection. All participants held the racket with their preferred grip and were not limited to a particular technique; however, they were requested to perform each shot at a speed similar to that within a game. The protocol for hitting shots was based on the HSAT and involved hitting the ball to a designated target area (Table 1). This protocol was chosen as it provided the participants with a purpose and aim to hit the ball, similar to within a match, and ensured consistency between participants (Elliott et al., 1988; Landlinger et al., 2010b). All participants were familiar with the test having performed it previously (average 7.7 ± 4.1 times). Target areas were marked on the court using masking tape as per Figure 1. Participants performed approximately 25 forehand shots of the "drive", "volley" and "drop" strokes (Table 1) in the middle of the court (Williams et al., 2018). The participants hit the drive and volley shots continuously to themselves (Table 1), while a coach with over 5 years experience running the HSAT fed the participants the ball for the drop shots. Participants had approximately 30 s between each different stroke test, to move from one area of the court to the next and prepare for the next stroke test. The five successful shots (balls that were hit within and landed in the designated target areas) with the least amount of broken trajectories, that were preceded by a successful shot, from each stroke for each participant were chosen for the purpose of analysis (Landlinger et al., 2012).

Data collection and analysis

Participants had 14 spherical reflective markers of 14 mm diameter attached to specific anatomical landmarks on their dominant upper-limb (Vicon upper-limb model marker set, as per Seminati et al. (2015)). This marker set included single anatomical and technical markers, as well as triad clusters of technical markers. Although highly dynamic movements can produce errors in marker tracking due to the movement of the skin and muscle (Gordon & Dapena, 2006), triad clusters of markers have been shown to produce more accurate results (Elliott et al., 2007) and reduce the effect of soft tissue artefacts (Cappozzo et al., 1995). The same upper-limb model has been used previously to evaluate shoulder and humerus rotations in

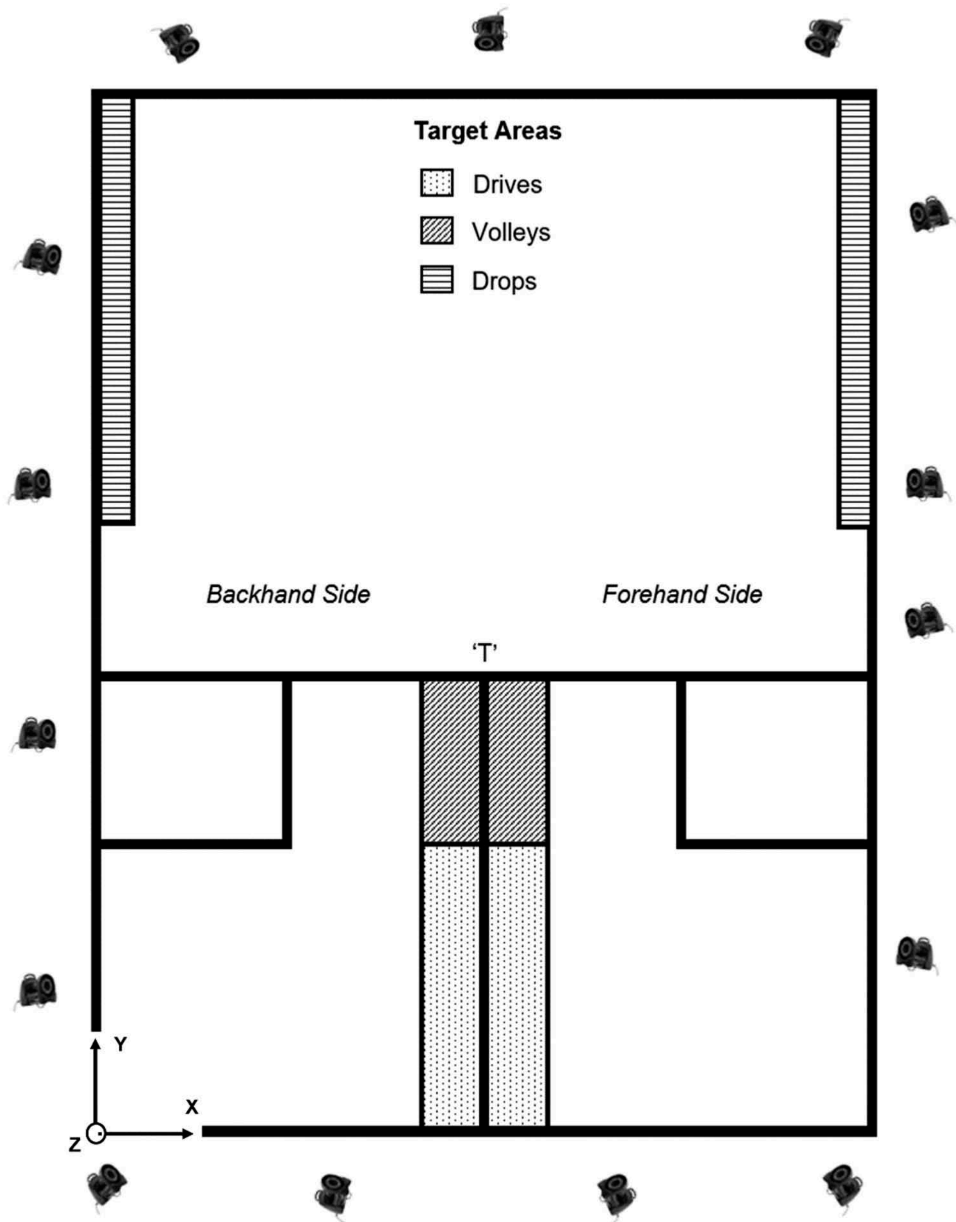

Figure 1. Target areas for the different strokes, camera set-up around the court and global coordinate system. The drop stroke target area was on the forehand side for the right-handed players and the backhand side for the left-handed players. Refer to Table 1 for dimensions of target areas.

Table 1. Shot type and corresponding protocol for the different strokes.

Stroke	Protocol
Drive	Hit continuously to self from behind the service box lines; the ball must not touch the back wall and must land within 0.5 m either side of the half court line (the initial hit is not counted)
Volley	Hit continuously to self from between the short line and service box lines; the ball must be hit within 0.5 m either side of the half court line (the initial hit is not counted)
Drop	Standing at the "T", the ball is fed to the player, who must play a drop shot; the ball's 2nd bounce must land within 0.35 m from the side wall and 1 m before the short line

volleyball (Seminati et al., 2015), overarm throwing technique (Taylor et al., 2015), water polo shot technique (Taylor et al., 2014) and hand-cyclist kinematics (Abel et al., 2010). Validation and additional information on the model can be found in Cutti et al. (2005) and Murray (1999). A further three reflective markers were attached to the top and mid-sides of the head of a racket. The marker set used on the racket was input into Nexus software (Nexus 2.2, Vicon Motion Systems, UK) and a rigid body model setup such that kinematic data could be collected at the same time as the other model. All data were collected via Nexus software.

The three-dimensional coordinates of the markers were reconstructed using Nexus software. The marker trajectories were labelled according to the model, with any broken trajectories filled using cubic spline interpolation. To avoid over-smoothing at impact, a second-order polynomial extrapolation estimated marker trajectories at impact (Reid et al., 2012). Following a residual analysis the data were filtered by a Woltring filter (Woltring, 1986) with a mean square error noise tolerance level set to 25 mm^2 and then joint positions calculated according to the respective models (Davis et al., 1991; Murray, 1999; Murray & Johnson, 2004).

Joint kinematics at the trunk, elbow and wrist were calculated using the Euler *xzy* sequence. Shoulder kinematics were calculated using an Euler decomposition of "plane of elevation", "elevation", "axial rotation" (Figure 2) in accordance with the International Society of Biomechanics recommendations (Seminati et al., 2015; Wu et al., 2005). The three racket head markers were used to produce projection angles relative to the global reference frame, with 0° indicating a fully "closed" racket face (face down and parallel to the floor) and 90° indicating an "open" racket face perpendicular to the floor (parallel to the front wall) (Kwon et al., 2017). The midpoint between the racket markers on the sides of the racket head (representing the middle of the racket head) was used to produce racket head linear velocity (Elliott et al., 1996). To ensure consistency in the statistical analysis, the kinematics for the two left-handed players were inverted where appropriate such that data from all players could be considered right-hand dominant (Whiteside et al., 2013b).

The kinematic parameters selected for analysis were based on previous squash and racket studies, which had shown variables to be important in stroke production, accurate shots, or contribute to racket head velocity (Ariff et al., 2012; Elliott et al., 1996; Landlinger et al., 2010a, 2010b; Marshall & Elliott, 2000), as well as discussions with international squash coaches. Orientation angles at impact, angular velocities at impact and ranges of motion (ROM) during the swing (from the top of backswing to impact) were calculated for: trunk rotation (relative to the global coordinate system, with 0° indicating an "open" trunk angle, parallel to the front wall, and 90° indicating a "closed" trunk angle, perpendicular to the front wall); shoulder plane of elevation; shoulder elevation; shoulder internal/external rotation; elbow flexion/extension; elbow internal/external rotation (forearm pronation/supination); wrist flexion/extension; and wrist abduction/adduction. Further to the upper-body kinematics, the following racket variables were calculated: racket head linear horizontal velocity; racket face projection angle (relative to the global reference frame in the Y-Z plane (Figure 1)); racket head velocity vector angle at impact (relative to the global reference frame in the Y-Z plane); racket-shoulder distance at impact (the distance between the racket head centre and shoulder joint centre in the global Y direction; positive if the racket was anterior to the shoulder); and racket head forward swing distance (the distance the racket head travelled in the global Y direction during the forward swing). All kinematic data were synchronised at ball impact (time = 0 s).

Statistical analysis

All kinematic data were analysed using SPSS Statistics software (IBM, version 22). Means and standard deviations were calculated for descriptive statistics. A two-way mixed analysis of

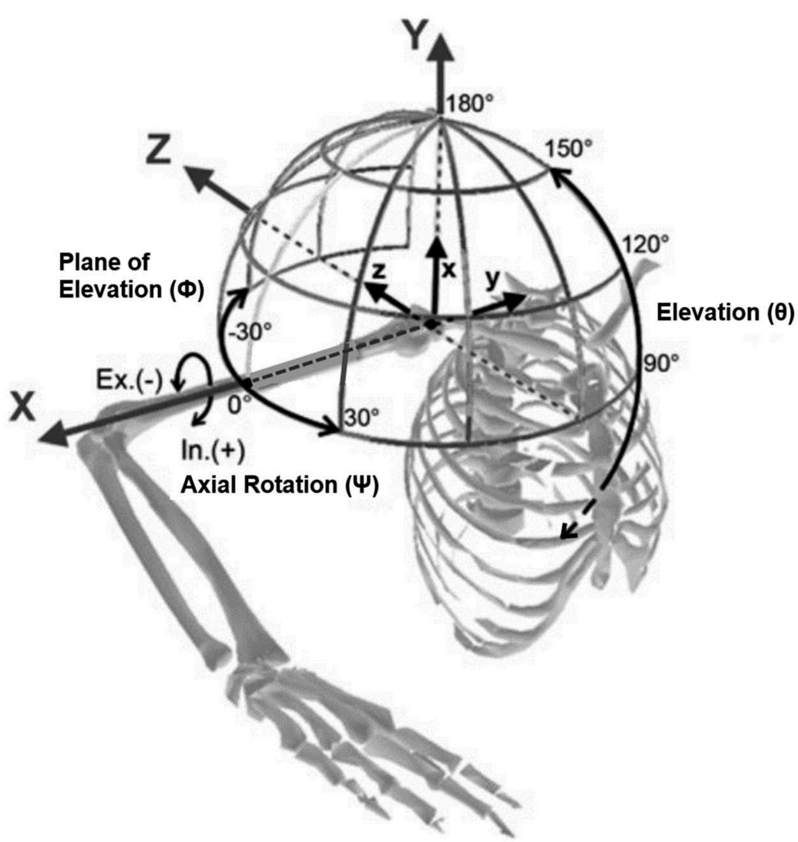

Figure 2. Coordinate system used to calculate joint kinematics at the shoulder. Shoulder YZ'Y": first rotation (Y) "plane of elevation" (Φ) about the Y (trunk anatomical frame); second rotation (Z) "elevation" (θ) about the z (shoulder anatomical frame); third rotation (Y) "internal/external axial rotation" (Ψ) about the y (shoulder anatomical frame). Adapted from "Shoulder 3D range of motion and humerus rotation in two volleyball spike techniques: injury prevention and performance" by E. Seminati, A. Marzari, O. Vacondio, A. E. Minetti, 2015, *Sports Biomechanics, 14*(2), 221.

variance with skill level (between participants: highly skilled and less-skilled) and shot type (within participants: drive, volley and drop strokes) were used to test for main effects and interactions. All variables were tested for sphericity before analysis and the 0.05 alpha level adopted to test significance. If a variable failed the sphericity test, then the Greenhouse-Geisser adjustment was employed. A Bonferroni posthoc multiple comparisons was performed if a significant main effect for stroke type or significant interaction between skill level and stroke type was observed. Effect sizes (partial eta squared, η^2) were considered as small (>0.01), medium (>0.06) and large (>0.14) (Cohen, 1988).

Results

Mean (± SD) values of all variables are shown in Table 2. All group effects and stroke effects for angles at impact, angular and linear velocities at impact, and range of motions and distance are shown in Tables 3–5 respectively. All significant main effects for group and stroke results were supported by large effect sizes.

Angles at impact

The within-participants analysis revealed a significant interaction effect (F = 4.31, p = 0.02, η^2 = 0.21) for trunk rotation angle, which showed the highly skilled group having a significant difference only between the drive and volley strokes, while the less-skilled had significant differences between all strokes (Table 3). The interaction effect also indicated the highly skilled group displayed a significantly (F = 6.41, p = 0.02, η^2 = 0.29) lower trunk rotation angle than the less-skilled during the drop stroke (~14°). The highly skilled group had significantly more wrist extension (~16°) and a smaller racket face angle (~4° less open face) than the less-skilled group across all strokes (Table 3).

Shoulder plane of elevation and internal rotation, elbow flexion and wrist extension angles were all significantly smaller in the drive compared to the other strokes. Shoulder elevation angle at impact was significantly higher during the drop stroke compared to the drive and volley strokes (~12°), while forearm pronation angle was significantly different between the volley and drop strokes only. Racket face angle and racket velocity vector angles were significantly different between all strokes, with the volley having the most "open face" position, moving in a slightly vertical direction (~6°); and the drop having the least "open face" moving in a more downwards direction (~ −23°) (Table 2).

Angular and linear velocities at impact

There was a significant interaction effect (F = 4.29, p = 0.02, η^2 = 0.21) for shoulder plane of elevation angular velocity. This indicated that the less-skilled group had a significant difference between drive and drop strokes and between volley and drop strokes, whilst the highly skilled group only displayed a difference between the volley and drop strokes (Table 4). There were no significant differences found between groups for any of the trunk or upper-limb angular velocity variables. A significant main effect (and no significant interaction) was found for horizontal racket velocity, indicating that the highly skilled group hit the ball faster than the less-skilled group (~1.6 m/s) for all strokes.

Trunk rotation angular velocity at impact was significantly slower during the volley compared to either of the other strokes (~ −62°/s). There was a significant difference between all strokes for shoulder internal rotation, elbow extension and forearm pronation angular velocity at impact, with the drive being the fastest and the drop being the slowest. The drive stroke displayed significantly faster wrist flexion angular velocity at impact compared to both the other strokes. Horizontal linear racket velocity was significantly different between all strokes with the order from fastest to slowest being: drive, volley, drop.

Range of motions and distance

The only variable that was significantly different between groups was forearm pronation/supination, with the highly skilled group having a greater ROM (~10°) for all strokes (Table 5).

There was significantly more trunk ROM in the drive stroke than the other strokes. Shoulder plane of elevation ROM was significantly smaller during the drop compared to the drive stroke, and the drop stroke also had significantly less ROM for shoulder internal/external rotation, elbow flexion/extension, forearm pronation/supination and wrist flexion/extension compared to both the drive and volley strokes (Table 5). The volley stroke had a significantly greater racket head forward swing distance than the drop stroke. Significant racket-shoulder differences were found between all strokes, the greatest value being in the volley and smallest in the drop stroke.

Discussion

The purpose of this study was to compare the trunk, dominant upper-limb and racket kinematics of highly skilled and less-skilled squash players in the forehand drive, volley and drop strokes, as well as identify any differences between strokes. An athlete's movements and rotations of their trunk and upper-limb segments play an important role in stroke production and ultimately control the critical factors of racket speed, trajectory and position at impact (Elliott et al., 1996). It appears evident that there are significant differences between the kinematics of the different skill groups and strokes.

Group differences

Knowledge of the differences in stroke kinematics between players of differing skill levels would provide insight into how the performance of less-skilled players can be improved, as well as enable greater specificity in squash swing mechanics development programmes. The findings in this study indicated that during the drop stroke, the highly skilled group hit the ball with a significantly more open trunk angle at impact compared to the less-skilled group. In fact, during the drop stroke, the less-skilled group displayed the most closed trunk angle at ball

Table 2. Mean (±SD) values for angles at impact, velocities at impact and range of motions.

		Highly skilled									Less-skilled								
		Drive			Volley			Drop			Drive			Volley			Drop		
Variable	Sig	Mean		SD	Mean		SD	Mean		SD	Mean		SD	Mean		SD	Mean		SD
Angle at impact																			
Trunk rot (°)	a c	−64.8	±	9.8	−52.7	±	12.7	−59.9	±	14.4	−65.0	±	9.8	−56.0	±	12.5	−74.2	±	8.9
Sh plane of elev (°)	a	76.6	±	8.0	79.1	±	9.5	81.1	±	6.6	67.8	±	10.6	75.6	±	10.3	78.4	±	5.4
Sh elev (°)	a	44.7	±	9.5	48.2	±	9.2	58.1	±	9.4	49.3	±	10.2	49.7	±	9.3	62.6	±	10.0
Sh internal rot (°)	a	−90.2	±	13.4	−93.8	±	13.5	−97.0	±	12.0	−84.7	±	15.4	−88.8	±	12.4	−91.1	±	7.3
Elb flexion (°)	a	32.8	±	7.5	41.0	±	6.3	44.2	±	7.4	35.9	±	7.2	46.0	±	9.4	42.9	±	6.0
Forearm pronation (°)	a	126.6	±	10.3	124.4	±	10.1	126.4	±	12.0	115.7	±	20.6	110.8	±	19.1	120.1	±	18.7
Wr extension (°)	a b	46.1	±	8.7	53.2	±	10.6	52.4	±	10.2	31.1	±	12.2	38.4	±	15.1	34.3	±	14.5
Wr adduction (°)		24.8	±	11.3	23.3	±	13.5	25.6	±	11.0	23.8	±	8.3	23.6	±	8.5	26.0	±	9.6
Racket face (°)	a b	119.3	±	2.2	122.9	±	3.2	111.8	±	3.9	123.2	±	4.2	127.1	±	3.4	115.1	±	1.6
Racket velocity vector (°)	a	−2.5	±	4.2	5.4	±	3.9	−24.7	±	3.4	0.1	±	1.9	6.6	±	3.1	−20.8	±	4.1
Velocity at impact																			
Trunk rot (°/s)	a	229.6	±	47.1	153.6	±	43.7	231.0	±	27.7	211.1	±	73.7	135.9	±	40.3	183.8	±	40.0
Sh plane of elev (°/s)	a c	69.8	±	81.5	46.5	±	104.3	103.4	±	84.0	−2.5	±	108.9	11.6	±	116.2	119.1	±	71.2
Sh internal rot (°/s)	a	858.7	±	314.4	554.5	±	201.6	196.9	±	141.6	956.8	±	346.9	638.3	±	215.8	201.8	±	67.3
Elb extension (°/s)	a	601.1	±	225.1	533.0	±	175.7	453.4	±	167.8	500.9	±	174.9	426.4	±	101.9	301.6	±	86.6
Forearm pronation (°/s)	a	622.9	±	278.1	419.5	±	124.5	271.3	±	138.8	540.9	±	288.0	296.7	±	205.0	151.0	±	90.6
Wr flexion (°/s)	a	407.8	±	152.7	362.6	±	169.9	317.7	±	67.7	443.9	±	101.6	332.2	±	114.0	256.7	±	74.5
Racket horizontal (m/s)	a b	25.4	±	1.9	20.1	±	1.3	12.6	±	1.3	23.6	±	2.0	18.6	±	2.0	11.2	±	1.1
Range of motion/Distance																			
Trunk (°)	a	35.3	±	11.7	23.9	±	9.0	33.4	±	12.2	43.6	±	13.7	25.1	±	10.3	28.4	±	9.4
Sh plane of elev (°)	a	51.0	±	11.8	45.5	±	10.9	40.3	±	15.8	59.4	±	11.6	57.9	±	6.1	45.8	±	12.9
Sh internal/ext rot (°)	a	51.2	±	4.5	48.4	±	8.7	32.4	±	7.0	51.7	±	10.2	51.4	±	11.9	30.8	±	10.5
Elb flexion/extension (°)	a	61.4	±	12.8	54.7	±	11.3	39.8	±	7.4	63.5	±	16.9	53.7	±	19.2	45.5	±	20.1
Forearm pronation/sup (°)	a b	38.7	±	7.9	36.6	±	5.5	26.1	±	5.2	29.1	±	7.8	23.6	±	8.5	17.8	±	7.2
Wr flexion/extension (°)	a	34.4	±	6.5	30.3	±	8.7	21.0	±	5.5	36.1	±	5.8	33.3	±	8.1	20.6	±	7.0
Racket swing dist. (m)	a	0.78	±	0.08	0.82	±	0.06	0.73	±	0.12	0.77	±	0.10	0.78	±	0.11	0.68	±	0.11
Racket-Sh impact dist. (m)	a	0.12	±	0.04	0.16	±	0.05	−0.01	±	0.04	0.10	±	0.08	0.17	±	0.08	−0.05	±	0.05

Sh = shoulder, Elb = elbow, Wr = wrist, rot = rotation, elev = elevation, ext = external, sup = supination, dist = distance, sig = significance.
*[a]significant stroke effect, [b]significant group effect, [c]significant interaction

Table 3. ANOVA main effects of angles at impact for group (between-participants) and stroke (within-participants) and post hoc results.

	Group Highly skilled vs Less-skilled				Stroke Drive vs Volley vs Drop					
Variable	*F*	*p*	η^2		*F*	*p*	η^2	*Dr-Vo*	*Dr-Dp*	*Vo-Dp*
Trunk rot (°)	1.67	0.21	0.10	[c]Dp	14.57	0.00	0.48	[c]hs, ls	[c]ls	[c]ls
Sh plane of elev (°)	2.24	0.15	0.12		7.53	0.00	0.32	a	a	
Sh elev (°)	1.03	0.32	0.06		16.57	0.00	0.51		a	a
Sh internal rot (°)	1.01	0.33	0.06		5.24	0.01	0.25	a	a	
Elb flexion (°)	0.61	0.45	0.04		19.82	0.00	0.55	a	a	
Forearm pro (°)	2.11	0.17	0.12		4.32	0.02	0.21			a
Wr extension (°)	8.85	0.01	0.36	b	9.39	0.00	0.37	a	a	
Wr adduction (°)	0.00	0.98	0.00		3.00	0.06	0.16			
Racket face (°)	13.35	0.00	0.46	b	73.60	0.00	0.82	a	a	a
Racket vel vector (°)	3.81	0.07	0.19		592.6	0.00	0.97	a	a	a

Note: hs = highly skilled, ls = less-skilled, Sh = shoulder, Elb = elbow, Wr = wrist, Dr = drive, Vo = volley, Dp = drop, rot = rotation, elev = elevation, flex = flexion, abd = abduction, pro = pronation.
[a]significant stroke effect, [b]significant group effect, [c]significant interaction.

Table 4. ANOVA main effects of velocities at impact for group (between-participants) and stroke (within-participants) and post hoc results.

	Group Highly skilled vs Less-skilled				Stroke Drive vs Volley vs Drop					
Variable	*F*	*p*	η^2		*F*	*p*	η^2	*Dr-Vo*	*Dr-Dp*	*Vo-Dp*
Trunk rot (°/s)	1.90	0.19	0.11		19.36	0.00	0.56	a		a
Sh plane of elev (°/s)	0.54	0.47	0.03		18.74	0.00	0.54		[c] ls	[c]hs, ls
Sh internal rot (°/s)	0.57	0.46	0.03		61.42	0.00	0.79	a	a	a
Elb extension (°/s)	2.74	0.12	0.15		31.17	0.00	0.66	a	a	a
Forearm pro (°/s)	2.46	0.14	0.13		21.60	0.00	0.58	a	a	a
Wr flexion (°/s)	0.16	0.70	0.01		12.42	0.00	0.44	a	a	
Racket horizontal (m/s)	9.19	0.01	0.37	b	313.7	0.00	0.95	a	a	a

hs = highlyskilled, ls = less-skilled, Sh = shoulder, Elb = elbow, Wr = wrist, Dr = drive, Vo = volley, Dp = drop, rot = rotation, elev = elevation, pro = pronation.
[a]significant stroke effect, [b]significant group effect, [c]significant interaction.

Table 5. ANOVA main effects of a range of motions and distance for group (between-participants) and stroke (within-participants) and post hoc results.

	Group Highly-skilled vs Less-skilled				Stroke Drive vs Volley vs Drop					
Variable	*F*	*p*	η^2		*F*	*p*	η^2	*Dr-Vo*	*Dr-Dp*	*Vo-Dp*
Trunk (°)	0.12	0.73	0.01		16.69	0.00	0.51	a	a	
Sh plane of elev (°)	3.84	0.07	0.19		9.21	0.00	0.37		a	
Sh int/ext rot (°)	0.03	0.86	0.00		43.23	0.00	0.73		a	a
Elb flex/extension (°)	0.12	0.73	0.01		27.64	0.00	0.63	a	a	a
Forearm pro/sup (°)	14.63	0.00	0.48	b	24.66	0.00	0.61		a	a
Wr flex/extension (°)	0.27	0.61	0.02		48.87	0.00	0.75		a	a
Racket swing dist. (m)	0.80	0.38	0.05		8.13	0.00	0.34			a
Racket-Sh impact dist. (m)	0.65	0.43	0.04		73.68	0.00	0.82	a	a	a

Sh = shoulder, Elb = elbow, Wr = wrist, Dr = drive, Vo = volley, Dp = drop, rot = rotation, elev = elevation, int = internal, ext = external, flex = flexion, pro = pronation, sup = supination, dist = distance.
[a]significant stroke effect, [b]significant group effect.

impact of both groups for all strokes. It is possible that the more open trunk position at impact was used by the highly skilled players to provide them with greater options for shot direction, similar to an open trunk position in tennis, which has been shown to provide court coverage advantages (Bahamonde, 2003).

Although the range of motion over which racket speed can be developed is crucial for producing powerful, fast strokes (Landlinger et al., 2010b), the highly skilled group did not demonstrate a greater racket head forward swing distance for any of the strokes. However, the less-skilled group did display approximately 10° less forearm pronation/supination ROM within all the strokes compared to the highly skilled group, a significant difference which could result in less speed being developed from this movement. Internal rotation of the forearm has previously been shown to be the third largest (~ 12%) upper-limb movement to contribute to linear racket velocity at impact in squash forehand drives (Marshall & Elliott, 2000).

The less-skilled group impacted the ball with a significantly smaller amount of wrist extension for all strokes, suggesting the ability to impact the ball with greater wrist extension was a trait indicative of a higher skill-level in the participants of this study. The elbow angles at impact recorded for the drive stroke in this study are comparable to those reported by Ariff et al. (2012); although Ariff et al. (2012), found a smaller wrist extension angle of only 12°, compared to the mean of 31.1° found in the less-skilled group of this study. However, the values reported by Ariff et al. (2012), were obtained from a single trial of one female intermediate athlete, while this study reports group mean values obtained from five trials of nine male athletes (per group). Furthermore, the wrist angle reported by Ariff et al. (2012) does fall within the range of values found for the less-skilled group within the present study.

The findings in this study indicated that the highly skilled group were impacting the ball using a similar racket velocity vector angle, yet with a faster horizontal racket velocity and a less open racket face than the less-skilled group across all strokes. Although ball mechanics were not measured in this study, it is possible that these differences in racket variables at impact could have resulted in the ball being hit faster and lower at the target area by the highly skilled group than the less-skilled. In a match situation, hitting the ball lower and faster to a strategically advantageous targeted area of the court could potentially result in less time for an opponent to hit the ball back, therefore putting them under more pressure and increasing the probability of an error, which could be a key element to skill level and success within a match (Landlinger et al., 2010b; Vučković et al., 2013). These findings are in agreement with other racket studies showing high correlations between racket velocity and skill level (Landlinger et al., 2010b; Nesbit et al., 2008; Sørensen et al., 2011). The highly skilled group's mean horizontal racket velocity for the drive stroke (25.4 ± 1.9 m/s) is lower than the 30.8 m/s reported by Elliott et al. (1996), however their participants were specifically instructed to hit a high-velocity shot (and were selected based on having a high-velocity drive), unlike this study where participants were hitting an accurate drive shot at a speed similar to within a match.

Stroke differences

The type of stroke played will generally dictate the swing path and impact characteristics used by an athlete in tennis (Elliott et al., 2009), and it appears the same principles apply to the different types of squash strokes. It is apparent that the ball was hit further from the body, with a straighter arm at impact, during the drive stroke than during the other strokes, as denoted by the significantly smaller impact angles for shoulder plane of elevation, elbow flexion and wrist extension. Additionally, the drive exhibited significantly greater trunk rotation and forearm pronation/supination ROM's, greater angular velocities at impact for shoulder internal rotation, elbow extension, forearm pronation, and wrist flexion, which may indicate a use of the kinetic chain model for power strokes (Elliott, 2006). These significant differences ultimately resulted in a faster horizontal racket velocity at impact in the drive than in the other strokes.

In previous studies, it has been proposed that internal rotation at the upper-arm, flexion at the wrist and forearm pronation are the largest contributors to racket velocity at impact, respectively, in the squash forehand drive stroke (Elliott et al., 1996; Marshall & Elliott, 2000). This contention is somewhat supported by the current findings, in that shoulder internal rotation and forearm pronation angular velocities became significantly faster from drop to volley to drive stroke, which led to a significantly faster racket impact velocity in the same order. Similarly, there were significantly greater elbow extension and wrist flexion angular velocities at impact in the drive than in the other two strokes, highlighting their potential important contribution to racket impact velocity.

Trunk rotation angular velocity at impact was the slowest during the volley stroke, significantly differing from both the other strokes; which could be partially attributed to the small trunk rotation ROM in that stroke. These findings may have resulted from the potentially shorter time the participants had to prepare for their shot. Although the time between the ball leaving the front wall and racket contact was not measured, standing further forward on the court for the volleys than the drives and hitting the ball on the full (without a bounce), may have reduced the time for backswing preparation and utilisation of trunk rotation. The racket head forward swing distance (from the top of the backswing to ball impact) between the volley and drive was similar, however, ball impact during the volley occurred with the racket significantly further forward of the shoulder (in the global Y direction), suggesting a shorter starting racket position (top of backswing) relative to the shoulder compared to the drive.

The ROMs of the upper-limb segments during the drop stroke were found to be significantly smaller than both the drive and volley strokes, which could account for the significantly smaller racket-shoulder distance at impact. The smaller ROMs could have also contributed to the significant decrease in angular velocities of the upper-limb segments, which ultimately resulted in a slower racket velocity at impact. Trunk rotation angular velocity at impact during the drop stroke however, was significantly faster than that of the volley and similar to the drive stroke. These findings may imply a tendency towards more of a precision stroke kinetic chain model in the drop shot, rather than a power stroke model (Elliott, 2006), whereby the upper-limb segments operated more as a single unit, with trunk rotation having a greater influence on racket velocity at impact. However, further analysis of the timing and contribution of peak upper-limb, trunk and lower-limb movements would be required to confirm this contention.

The trajectory of the racket head at impact during the drop stroke was significantly more angled below the horizontal (downward) than the other strokes, and when combined with the more vertical racket face angle at impact, imply somewhat of a "slice" action. It has been previously shown that with the correct combination of downward racket trajectory and racket face angle at ball impact it is possible to impart backspin on a tennis or table tennis ball (Elliott & Christmass, 1995; Iino et al., 2008). Although ball mechanics were not measured in this study, it is plausible that the combination of racket angle and trajectory at impact allowed the players to apply backspin to the ball to enhance the effectiveness of their drop shots (Elliott & Christmass, 1995).

This study was delimited to a kinematic analysis of the upper-body and as such, an analysis of the lower body was outside the scope of the present study. There have been very few studies that have evaluated the role of the lower body in squash stroke production, however, the kinematics of the lower body have been shown to play a role in successful tennis ground-strokes (Elliott, 2006). Therefore, it is recommended that future investigations be undertaken to determine the role the lower body plays within different squash strokes. The present study also did not measure any ball mechanics such as; speed, trajectory or spin, nor did it consider the effect of racket properties on the resulting shots.

These limitations should be considered when interpreting the findings.

There is currently a lack of literature evaluating the swing kinematics of players of differing skill levels across different squash strokes, making it difficult to compare many of the findings from this study to previous results. However, it is anticipated that this initial evaluation will provide relevant information to sport scientists and coaches that can be expanded upon to advance the understanding of the kinematics of squash strokes. It is envisioned that this research will be followed by additional investigations into the accuracy of squash shots for the purpose of distinguishing accurate and inaccurate shot technique. It is also recommended that further work be carried out on additional populations and skill levels, as well as evaluating the kinematics of other squash strokes such as the boast, lob or the backhand and crosscourt variations of the strokes analysed in this study.

Conclusion

The findings from this study indicated that the highly skilled group displayed a less open racket face and faster horizontal racket velocity at impact than the less-skilled group for all strokes. The between-stroke comparisons revealed that drive shots were hit utilising greater upper-limb segment angular velocities that resulted in a faster and flatter racket impact velocity than the other strokes. During the volley, ball impact occurred from a more open trunk position, utilising less trunk rotation angular velocity and a more open racket face than the other strokes. The drop shots had smaller upper-limb ROMs than both the volley and drive shots, which resulted in lower upper-limb angular velocities at impact compared to the other strokes.

The knowledge obtained from this study, combined with existing information, should provide coaches and sport scientists with a better comprehension of the kinematic differences between players of different skill levels and of the technique differences between strokes. This novel information can enable the construction of more specific stroke technique programmes to progress players' swing mechanics.

Acknowledgments

The authors would like to thank squash Head Coach Stewart Boswell for his assistance with the data collection and the athletes who volunteered to participate in the study. The publication of this article was funded by the Qatar National Library.

Disclosure Statement

The authors report no conflict of interest.

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