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QUANTIFYING MOTION AND 'T' DOMINANCE OF ELITE SQUASH PLAYERS

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ABSTRACT

Advances in video analysis technology expand the realm of possibility for analyzing sport tactics and motion. Video analysis techniques are especially effective in squash due to the small, well-lit, defined court, paired with an ever-growing video collection of elite tournament matches. The availability of matches enables a new methodology that requires no special setup, but only uses video analysis software and the recorded matches that are conveniently filmed for entertainment purposes. This paper presents and evaluates this new methodology that encompasses distance travelled, velocities and speeds attained, court position, and 'T' dominance in elite squash. The method was validated when results were compared to previous studies, and a correlation between world rank and court dominance was measured for the first time. A strong correlation (r = 0.64, p<0.001) was found between world rank and average distance from an optimal court position known as the 'T' of the squash court.

Keywords: kinematics, racket sports, video-analysis, video-tracking, Sports Performance

INTRODUCTION

Squash is classified as one of the 4 major racquet sports, alongside badminton, tennis, and table tennis (Lees, 2003). These racquet sports have been played and enjoyed for more than 130 years (Lees, 2003). They are characterized by the use of a hand-held racquet to propel a projectile in such a way that the other player cannot successfully return it, while remaining within the confines of the specified court (Lees, 2003). Racquet sports require excellent hand-eye coordination and a skill set that includes power, accuracy, agility, and determination. Squash is a high-paced racquet sport played in a 4-walled court. What makes squash uniquely exciting is that opponents stand side by side rather than stand on opposing sides of the court separated by a net. Players must take turns keeping the ball in play by hitting it to the front wall within the bounds of play, rather than clearing an obstacle separating the players as seen in the other major racquet sports. While squash has been around since 1830 (Wallbutton, 2015), there are very limited studies evaluating the kinematics and kinetics associated with squash. However, recent advances in video analysis software, along with the availability of video recorded world tournament matches enable a quantitative analysis of the kinematics and kinetics of match play.

Previous studies have investigated distance covered and average velocities of match play (and individual rallies), and the correlation to the outcome of the match (or rally) (Hughes and Franks, 1994; Vučković *et al.*, 2003; Vučković *et al.*, 2009). Hughes and Franks (1994) used video images of squash matches and mixed them with coordinates recorded by an observer using a digitizing pad and stylus, similar to that described in Franks, Wilson, and Goodman (1987). They explored the lateral and longitudinal position, velocity, and accelerations in the last ten seconds of a rally for players of varying standard. They concluded that elite players exhibited significantly greater velocities and accelerations at the end of a losing rally than at the end of a winning rally (Hughes and Franks, 1994). While this confirmed the presumption held by Hughes and Franks that the winning player moves less due to court dominance and control, Vučković *et al.* (2003) found results based on a full match movement analysis that conflicted with this presumption, to the authors' surprise.

Vučković *et al.* (2003), Vučković and James (2010) expanded on the ideas of Hughes and Franks (1994) to analyze squash not only at the rally level, but entire match play as well. These studies utilized a new method of real-time data acquisition called SAGIT/Squash tracking system. The system obtains color images from a birds-eye camera view positioned above the court with players, and compares them to an empty court image to determine the approximate position of the players (Vučković *et al.*, 2003; Vučković and James, 2010; Perš *et al.*, 2001). The full match analysis by Vučković *et al.* (2003) resulted in highly varying match times, percent of active match play, distances, and velocities. Although the distances travelled by players in a single game was similar, the games sampled in this study showed the winners travelled *greater* distances in 18 of 24 games (Vučković *et al.*, 2003). These results (although not statistically significant) were surprising and contradicting to the authors' beliefs, which surmised that the winners would cover less ground, and have a lower speed on average. Vučković and James (2010) went on to analyze all the rallies in 11 matches that took place at the 2003 World Team Championships. On average, rally winners covered 0.71 m less than losers. However, in 41.4% of rallies analyzed, the winner travelled more than the loser (Vučković and James, 2010).

Court position relative to the 'T' of the squash court (near-centre court position) was also investigated. The T is where squash players seek to position themselves in between shots in order to be in a neutral position that is favourable for returning any type of shot (Vučković *et al.*, 2009). Analyzing the elite players' positions relative to the T can help quantify where players either prefer to stand or are forced to move most frequently due to an opponent's shot placement. Vučković *et al.* (2009) sampled World Team Championship matches (n = 11), Slovenian National Championships (n = 11), and a local tournament (n = 15), which all took place in 2003. (Note that in 2003 the system of point-a-serve was in place). They found that winners spent a larger proportion of match play in the T area than losers, except during closely contested games. This held true for all 3 distinct levels of playing standard. These results suggest that time spent in the T area indicates dominance of rally (Vučković *et al.*, 2009). Thus, if both players spend around the same amount of time in the T area, the players are likely of similar skill level and both capable of winning the game.

The conclusion of the above mentioned studies is that there appears to be no direct correlation between distance travelled or average velocity and the outcome of the rally or game. Even though a player can be dominating the court and controlling the T, they can still make an error that gives the point to their opponent, regardless of distances travelled. In this study, we propose a new methodology that does not require any special setup such as a digitizing pad (Hughes and Franks, 1994; Franks *et al.*, 1987; Hughes *et al.*, 1989) or a ceiling mounted camera (Vučković *et al.*, 2003; 2009; Vučković and James 2010; Perš *et al.*, 2001) but rather uses elite tournament match videos already recorded by the Professional Squash Association (PSA). This new methodology removes the limitation of live data acquisition held by previous studies. Removing the requirement of equipment setup and real time data collection immensely expands the available matches to acquire data from. Any match that has been filmed by the PSA (or any match that has been filmed suitably) is now available to be analyzed with our methodology. The objective of this study was to test and compare the results of our new methodology with the results of the few previous studies (Hughes and Franks, 1994; Vučković *et al.*, 2003; 2009; Vučković and James 2010) that quantify the kinematics of squash. This study is the first to compare PSA rank assigned to elite level squash players as a variable in distance travelled, average velocity, and position relative to the T. Our study is also the first to obtain results of elite squash kinematics for a full match after the current point-a-rally system had been adopted.

METHODS

The research protocol was submitted to the health research ethics board. According to article 2.2 of the Canadian Tri-Council policy, research that relies exclusively on publicly available information is not required to go through the full research ethics board review and approval.

Professional world tournament squash matches were purchased from the Professional Squash Association (PSA) and analyzed in this study. This study sampled 5 matches (Table 1) consisting of 20 games from the years 2012-2014, and 6 different players. Player skill level varied from rank number 1 in the world to rank number 53. A player's ranking at the time of play was obtained from the player's ranking history retrieved from: http://www.squashinfo.com/rankings. Matches were chosen to compare top ranking players (top 5) against each other, and against lower ranked players (between 18 and 53). The full-length video of the match was cropped to only contain match play. Match play was recorded by PSA using 3 cameras: a full court view main camera, a close up camera, and a left sidewall camera. Only active match play from the main camera was analyzed since the other two views did not contain the whole court. The footage was available at 25 frames per second.

Table 1. Matches analyzed in this study.

Tournament	Date	# of Games	Stage	Player 1 (rank)*	Player 2 (rank)*
El Gouna International	April 2014	4	Finals	Ashour (4)	El Shorbagy (3)
Canary Wharf Classic	March 2013	5	Quarter Finals	El Shorbagy (5)	Mustonen (53)
Swedish Open	February 2013	5	First Round	Pilley (18)	Mustonen (51)
North American Open	February 2013	3	Second Round	Willstrop (3)	Rodriguez (25)
North American Open	February 2013	3	Second Round	Ashour (1)	Pilley (19)

**PSA Rank at time of match. Player 1 was the winner of the match.*

Video analysis software, Dartfish® Team Pro version 8 (2015) was used to obtain 2D coordinates of each player's feet in every frame of the video image. Using the software, a marker was placed on each foot for every frame in the video. The software was semi-automatic, with frequent user intervention. The software used the video image pixel coordinates to calculate output coordinates of the tracked markers in the plane of the camera view. The coordinates of the tracked markers were recorded at each frame in the video and exported to Microsoft Excel. The exported video image coordinates were multiplied by match-specific mathematical equations that converted from the video image coordinate system to the coordinate system of the plane of the court. The one-to-one coordinate system mapping transform between the court floor coordinate system and the video image coordinate system was obtained using the known coordinates of the permanent locations on the court floor (service lines and corners) and three coordinate systems. The first was the coordinate system of the plane of the court. The second was the viewing camera coordinate system (whose origin was the camera). The third was the video image coordinate system. The first coordinate system was chosen such that the third axis was perpendicular to the plane of the court, i.e., a point on the court has coordinates $\mathbf{x} = \begin{pmatrix} x \\ y \\ 0 \end{pmatrix}$. If $\mathbf{x}' = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}$ represents the coordinates of the point X in the camera coordinate system, then the relationship between $\mathbf{x}'$ and $\mathbf{x}$ is given by:

$$\mathbf{x}' = \mathbf{Q}\mathbf{x} + \mathbf{c} \quad (1)$$

where $\mathbf{Q}$ is a rotation matrix defined by three angles θ_x, θ_y, and θ_z while $\mathbf{c}$ is a translation vector defined by three components c_x, c_y, and c_z.

If $\mathbf{x}'' = \begin{pmatrix} x'' \\ y'' \end{pmatrix}$ is the vector of coordinates of a point in the plane of projection of the camera (video image coordinate system), then:

$$\frac{x''}{d} = \frac{x'}{z'} \qquad \frac{y''}{d} = \frac{y'}{z'} \quad (2)$$

where d is the focal length of the camera. There are seven unknowns in the above equations: $\theta_x, \theta_y, \theta_z, c_x, c_y, c_z$, and d.

The unknowns can be obtained by using the known court coordinates and video coordinates of the following 10 points on the court: The four corners, two corners from each of the two service boxes, and the T. By minimizing the square of the error in the video coordinates of 10 points, the seven unknowns are obtained.

After finding the seven unknowns describing transformation, the transformation equation from the projection of the court on the video coordinate system to the actual court coordinate system can be obtained by inverting the above relationships. First, the equation of the court plane $z'(x', y')$ was obtained by setting $z = 0$ in Equation 1 by assuming that the feet of the players slide along the plane of the court floor. By substituting $z'(x', y')$ in Equation 2, the inverse of Equation 2 can be obtained, i.e., $\mathbf{x}'(\mathbf{x}'')$. Then, the inverse of Equation 1 can be obtained simply as, $\mathbf{x} = \mathbf{Q}^T(\mathbf{x}' - \mathbf{c})$. Therefore, the final equation has the form:

$$\mathbf{x} = \mathbf{Q}^T(\mathbf{x}'(\mathbf{x}'') - \mathbf{c}) \quad (3)$$

The position of the feet in each frame can be obtained using Equation 3 and therefore the distance travelled throughout the duration of a game can be evaluated. The distance travelled in one game is equal to the sum of displacements in each frame of the game. Coordinates of a player's left and right feet were averaged to approximate the player's centre of mass coordinates, which was then used for analysis. Displacement in each frame was calculated from the change in coordinates from one frame to the next using the Euclidian norm.

Position relative to the T was calculated by placing the court floor coordinate system's origin at the T (x increasing to the right and y increasing to the front wall). The percent of time spent left, and behind the T in match play was calculated using this origin. Taking the Euclidian norm of a player's coordinates calculated their radial distance from the T (McGarry *et al.*, 1999). Percent of time spent left of the T was calculated as number of data points with negative x-values divided by total data points. Similarly, percent of time spent behind the T was calculated as number of data points with negative y-values divided by total data points.

The average velocity component for each frame was calculated as the corresponding displacement component in that frame divided by the duration of a frame (1/25 s). Velocity components were calculated separately using the change in the x-coordinate and the change in the y-coordinate, respectively, divided by the frame duration. The Euclidian norm of the velocity vector was taken to determine the speed of the player at every frame.

The frequency plots belonging to the players speeds followed a gamma distribution that was described through parameters of shape (k) and scale (θ). The shape and scale parameters can be estimated using a maximum likelihood estimator (Minka, 2002). The mean speed was equal to the product of the distribution parameters $(k\theta)$. The variance of a gamma distribution was equal to $k\theta^2$.

As mentioned previously, only the time when the ball was in play was analyzed. Thus, there were gaps in the time between sets of data for one game due to stop of play between rallies. There were also gaps in time from when the secondary (and unanalyzed) camera views were used. The number of rallies in a game was approximated with the use of an algorithm created in Microsoft Excel. If the gap in time between sets of data for one game exceeded 5 seconds, it was assumed that was the end of a rally and a beginning of a new one, rather than just a switch to and from a secondary camera.

Simple linear regression models were established to determine the effect of player rank or outcome of game on any of the various measured parameters: average radial distance from the T, total distance travelled, average speeds before and after removing speeds <1 m/s, speed distribution parameters before and after removing speeds <1 m/s. The significance level was set at α = 0.05. 95% confidence intervals were found for significant correlations.

Only active match play was analyzed in this study and all values reported correspond to when the ball was in play. The length of active match play time varied with each match. The percent of active match play that was analyzed changed depending on how often the camera view switched from the full court main camera view to the other secondary camera views. Length of match was taken to be the duration of time spanning the beginning of the first game to the end of the last game in a match, including the breaks between games (set at 90 seconds by the tournament rules). Length of active match play is the sum of time when the ball was in play. The percent of analyzed match play was calculated as the length of active match play filmed from the analyzed main camera view, divided by length of active match play.

RESULTS

The summary of all match lengths, % active, and % analyzed are tabulated in Table 2. The mean amount of active play in a match was 23.7 minutes. The mean amount of analyzed active play was 81.2%.

Table 2. Match length, active match play, and % of analyzed active match play.

Tournament	# Of Games	Players	Match Length In Minutes	Minutes (%) Of Active Match Play	% Of Analyzed Active Match Play
El Gouna International	4	Ashour vs El Shorbagy	71.3	30.0 (42.1%)	80.5%
Canary Wharf Classic	5	El Shorbagy vs Mustonen	51.5	23.5 (45.6%)	73.0%
Swedish Open	5	Pilley vs Mustonen	63.9	32.3 (50.5%)	87.7%
North American Open	3	Willstrop vs Rodriguez	37.2	15.55 (41.8%)	82.5%
North American Open	3	Ashour vs Pilley	41.1	17.3 (42.1%)	79.9%
AVERAGE	4	\	53	23.7 (44.8%)	81.2%

The coordinate system mapping equations were successful in changing the skewed video image coordinates to the corresponding squash court coordinates.

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Court specific equations were created since the camera's position relative to the court varied slightly with each tournament. The average of absolute errors in predicting known points on the court floor used to create the equations was 0.04 m in the x direction (lateral) and 0.09 m in the y direction (longitudinal). The maximum error arose from predicting the front right corner where the y-coordinate was underestimated by 0.40 m. All errors in predicting known points on the court floor that created the equations are tabulated in Table 3.

Assuming the games are independent of one another, individual mean game values follow a normal distribution and an overall average for each observed variable can be obtained. Table 4 outlines the mean and standard deviation of variables for all analyzed games winners, losers, and all players.

Table 3. Errors in predicting court locations that were used to create coordinate system mapping equations.

Key Points	North American Open 2013		Swedish Open 2013		Canary Wharf Classic 2013		El Gouna International 2014	
	x-Error (m)	y-Error (m)	x-Error (m)	y-Error (m)	x-Error (m)	y-Error (m)	x-Error (m)	y-Error (m)
1	-0.09	-0.05	-0.08	-0.04	-0.00	0.16	-0.06	-0.02
2	0.04	0.13	0.03	0.12	0.06	0.30	0.02	0.21
3	-0.05	-0.15	-0.04	-0.01	-0.09	-0.40	-0.09	-0.08
4	-0.02	0.04	-0.02	0.00	-0.04	-0.04	0.06	0.30
5	-0.02	0.01	-0.02	0.01	-0.04	0.02	0.12	0.10
6	0.03	0.01	0.03	0.04	-0.01	0.01	-0.04	-0.25
7	0.03	0.03	0.02	0.03	0.12	-0.03	0.10	0.31
8	0.06	0.03	0.06	-0.00	-0.09	-0.12	-0.04	-0.26
9	0.02	0.04	0.04	-0.01	-0.02	0.01	-0.07	-0.15
10	-0.01	-0.09	-0.02	-0.04	0.13	0.07	0.00	-0.03

Table 4. Overall mean value and standard deviation of game averages.

Variable	Winners	Losers	All Players
Distance Travelled (m)	537 ± 182	541 ± 184	539 ± 181
Radial Distance to T (m)	1.76 ± 0.11	1.84 ± 0.13	1.80 ± 0.13
% Spent Left of T	58.4 ± 4.4	56.3 ± 6.3	57.3 ± 5.5
% Spent Behind T	88.6 ± 4.6	89.9 ± 4.7	89.3 ± 4.7
Speed (m/s)	1.87 ± 0.07	1.88 ± 0.07	1.88 ± 0.07
% speeds > 9 m/s	0.24 ± 0.12	0.27 ± 0.13	0.25 ±0.13
Speed (excluding < 1.0) m/s	2.50 ± 0.07	2.54 ± 0.08	2.52 ± 0.07
% speeds < 1 m/s	30.8 ± 2.1	31.5 ± 1.5	31.2 ± 1.8

Of all the analyzed games, the distance travelled ranged from 338 m to 982 m. No statistical significance was found in the correlation between distance travelled and

PSA rank or outcome of the game. Table 5 reports distance travelled by winners and losers in every game.

Table 5. Distance travelled by game winners, losers, the difference between them, and number of rallies approximated with the algorithm.

Players (rank)	Game #	Game Winner (m)	Game Loser (m)	Difference (Winner - Loser) (m)	Rallies
Ashour* (4) vs. El Shorbagy (3)	1*	786	812	-26	25
	2*	982	958	23	40
	3	377	376	1	20
	4*	487	507	-20	24
	5	\	\	\	\
El Shorbagy* (5) vs. Mustonen (53)	1	383	367	17	13
	2*	390	369	21	21
	3	410	395	15	21
	4*	392	410	-18	24
	5*	338	341	-3	24
Pilley* (18) vs. Mustonen (51)	1*	884	873	11	22
	2	538	565	-27	22
	3	564	617	-52	19
	4*	665	671	-6	21
	5*	465	431	34	14
Willstrop* (3) vs. Rodriguez (25)	1*	510	555	-44	21
	2*	556	590	-34	21
	3*	350	359	-9	14
	4	\	\	\	\
	5	\	\	\	\
Ashour* (1) vs. Pilley (19)	1*	569	546	23	22
	2*	408	380	28	18
	3*	696	691	6	27
	4	\	\	\	\
	5	\	\	\	\
AVERAGE (Standard deviation)		**537 (±182)**	**541 (±184)**	**-3 (±25)**	**21.7 (±5.7)**

**The asterisk marks the winner of the match and which games they won in the match.*

Average radius to the T maintained in a game ranged from a minimum of 1.53 m to a maximum of 2.02 m. Table 6 reports all average radii to the T, % spent left of T, and % spent behind the T, for each game's winner and loser. Figure 1 shows the sinusoidal nature of two player's radius to the T as the rally progresses; one player reaches a maximum distance from the T while the other reaches a minimum. A strong positive correlation between rank and average *game* radial distance from the T was found; $r = 0.64$, $p<0.001$, 95% CI [0.0025,0.0056]. Furthermore, a stronger positive correlation was found between rank and average *match* radial distance from the T; $r = 0.69$, $p<0.05$, 95% CI [0.00054,0.0073]. A weak to moderate correlation was found between mean T radius and outcome of the game (win or loss); $r = 0.33$, $p<0.05$, 95% CI [-0.158, -0.005].

The speed frequency distributions belonging to the players' game speeds follow a gamma distribution with parameters of shape and scale. Examples of 2 player's speed frequency distributions can be seen in Figures 2 & 3. Speeds larger than 9 m/s were considered outliers and were removed (0.25% of data on average) (Weyand *et al.*, 2000).

Figure 1. An example of two players' radii to the T during a typical rally.

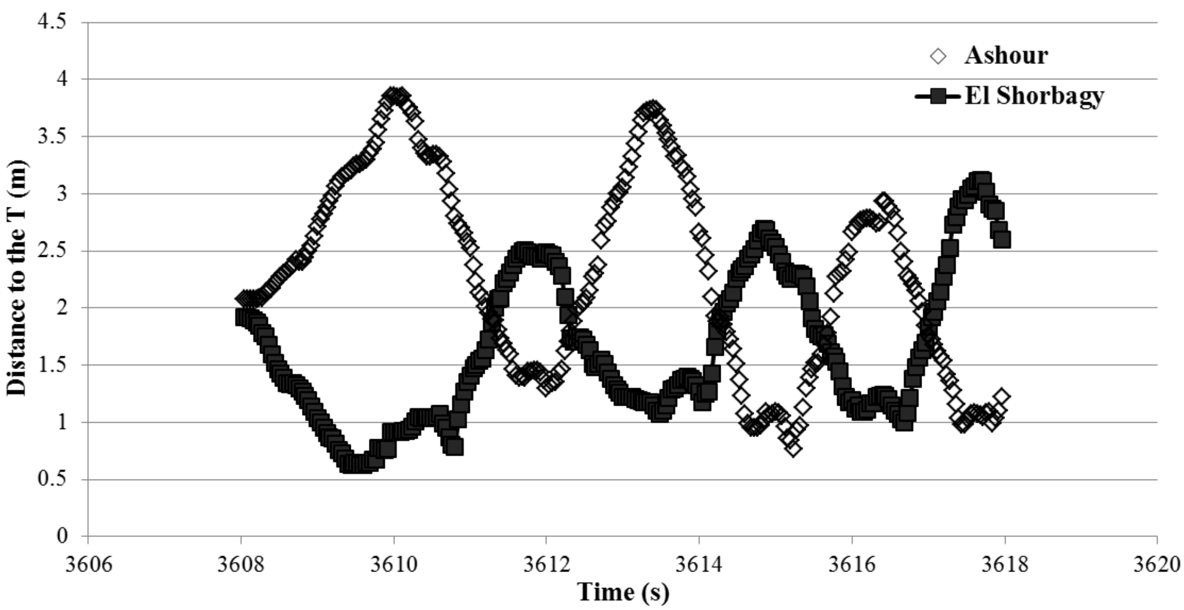

Figure 2. Frequency of Ashour's speeds from game 4 of El Gouna 2014 final put into 0.5 m/s spaced bins.

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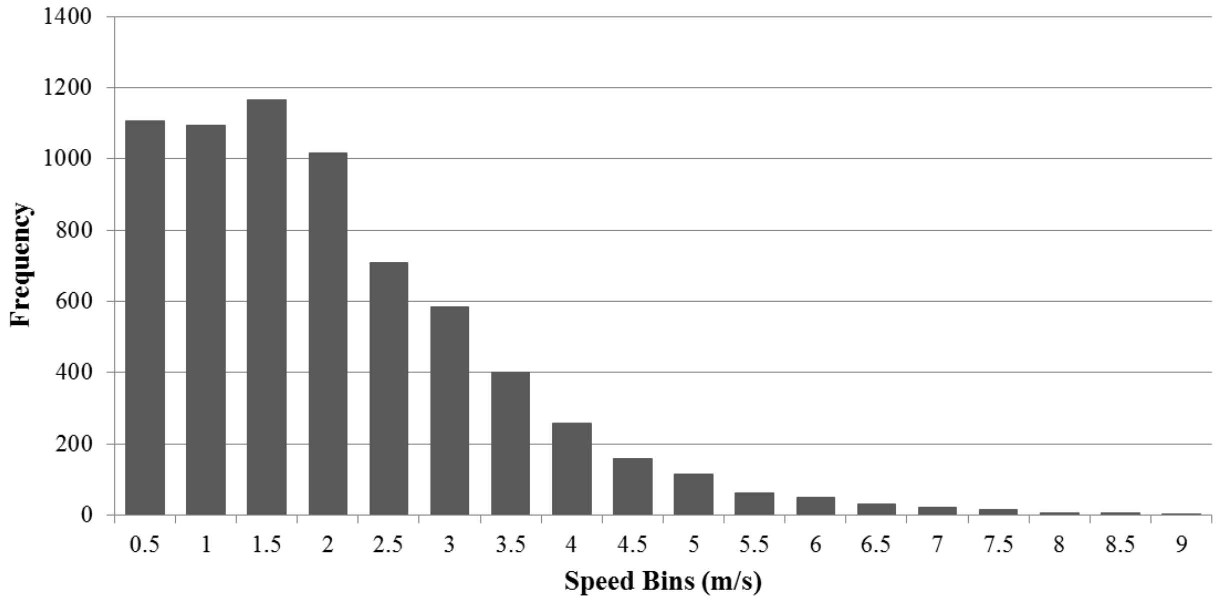

Figure 3. Frequency of El Shorbagy's speeds from game 4 of El Gouna 2014 final put into 0.5 m/s spaced bins.

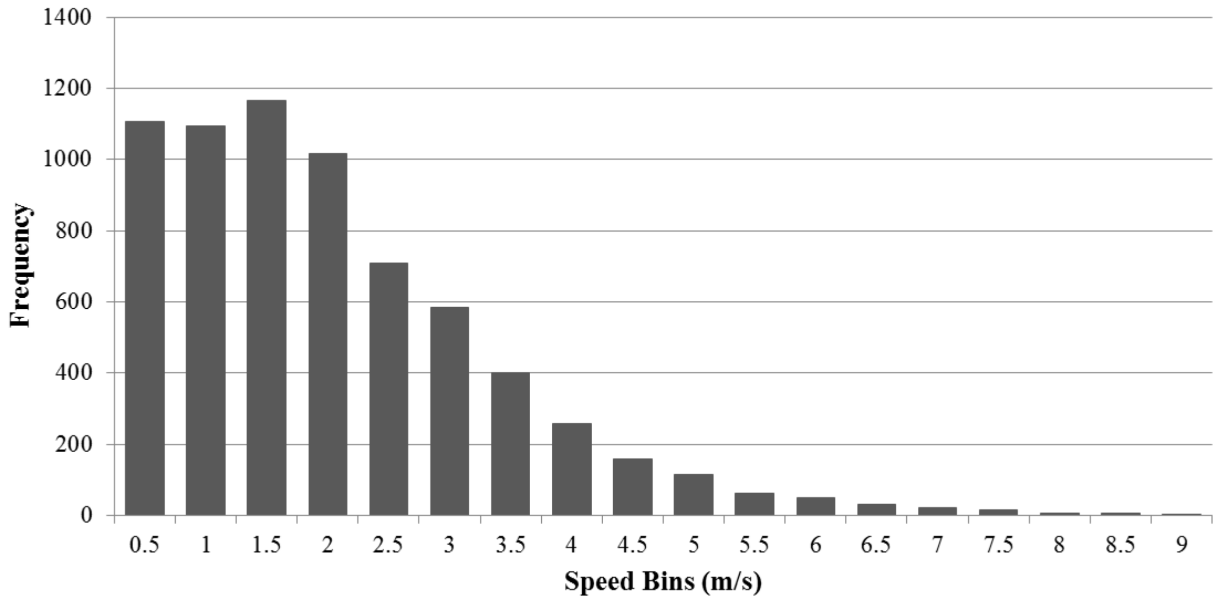

Table 6. Average distance to the T, % Left of T, and % Behind T for the winners and losers of each game.

Tournament	Game #	Average Radial Distance to T (m)		% Left of T		% Behind T	
		Winner	Loser	Winner	Loser	Winner	Loser
Ashour* (4) vs. El Shorbagy (3)	1*	1.65	1.68	54.6	49.9	93.2	89.2
	2*	1.75	1.71	58.6	55.7	94.3	92.9
	3	1.75	1.77	55.3	50.5	84.6	87.8
	4*	1.73	1.81	52.3	54.4	92.9	92.1
	5	\	\	\	\	\	\
El Shorbagy* (5) vs. Mustonen (53)	1	1.90	1.85	52.8	53.2	94.8	92.5
	2*	1.82	1.85	56.2	53.7	85.4	91.9
	3	1.91	1.69	50.0	48.1	94.1	86.9
	4*	1.53	1.98	59.0	58.7	80.7	90.0
	5*	1.65	2.02	64.9	68.7	87.8	92.6
Pilley* (18) vs. Mustonen (51)	1*	1.79	1.96	61.9	61.5	84.6	94.3
	2	1.77	1.79	65.6	68.3	88.7	82.4
	3	1.88	1.79	63.3	65.8	93.9	86.7
	4*	1.72	2.02	63.5	62.0	84.7	94.1
	5*	1.72	2.02	61.8	61.1	87.0	96.6
Willstrop* (3) vs. Rodriguez (25)	1*	1.70	1.93	55.5	53.3	88.5	93.1
	2*	1.74	1.94	56.9	51.1	84.8	90.9
	3*	1.59	1.99	57.7	52.6	83.2	93.3
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
Ashour* (1) vs. Pilley (19)	1*	1.91	1.69	58.5	51.6	95.9	90.1
	2*	1.85	1.64	56.5	50.6	88.7	83.1
	3*	1.86	1.70	63.0	54.6	84.8	77.2
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
AVERAGE (standard deviation)		**1.76 (±0.11)**	**1.84 (±0.13)**	**58.4 (±4.4)**	**56.3 (±6.3)**	**88.6 (±4.6)**	**89.9 (±4.7)**

**The asterisk marks the winner of the match and which games they won in the match.*

The maximum and minimum mean speeds recorded were 2.04 m/s and 1.73 m/s. Table 7 reports mean speeds, speed distribution parameters, and % of excluded data (> 9.0 m/s) for all games winners and losers. No statistically significant correlation was found between mean speed or distribution parameters with PSA rank or outcome of game.

After excluding the 0 – 1.0 m/s range, the maximum and minimum mean velocities then became 2.65 m/s and 2.38 m/s, respectively. The percent of active play spent under 1.0 m/s was 30.8 (±2.1) % for winners and 31.5 (±1.5) % for losers. Table 8 reports mean speed, speed frequency distribution parameters, and % of excluded data for the winners and losers of each individual game.

The algorithm created for counting rallies was useful in approximating number of rallies automatically, without manually counting them. In a sample game, the algorithm calculated 24 rallies, which is very close to the manually verified number of 23. The average number of rallies was 21.7 (±5.7). The amount of rallies approximated for each game can be found in Table 5.

Table 7. Mean speed, speed distribution parameters, and excluded data for winners and losers.

Players (rank)	Game #	Mean speed (standard deviation) m/s		Speed distribution parameters k, θ		% of outliers >9 m/s	
		Winner	Loser	Winner	Loser	Winner	Loser
Ashour* (4) vs. El Shorbagy (3)	1*	1.90 (1.49)	1.95 (1.60)	1.64, 1.16	1.48, 1.31	0.40	0.57
	2*	1.88 (1.52)	1.84 (1.56)	1.54, 1.22	1.39, 1.33	0.14	0.14
	3	1.83 (1.55)	1.84 (1.54)	1.39, 1.31	1.42, 1.29	0.12	0.06
	4*	1.78 (1.44)	1.84 (1.57)	1.54, 1.16	1.37, 1.34	0.09	0.28
	5	\	\	\	\	\	\
El Shorbagy* (5) vs. Mustonen (53)	1	1.82 (1.46)	1.73 (1.48)	1.54, 1.18	1.38, 1.25	0.23	0.33
	2*	1.93 (1.58)	1.83 (1.57)	1.49, 1.29	1.35, 1.35	0.51	0.36
	3	1.85 (1.49)	1.77 (1.52)	1.53, 1.20	1.37, 1.30	0.09	0.11
	4*	1.79 (1.51)	1.88 (1.54)	1.50, 1.25	1.42, 1.27	0.43	0.47
	5*	1.88 (1.65)	1.91 (1.55)	1.50, 1.26	1.29, 1.46	0.27	0.13
Pilley* (18) vs. Mustonen (51)	1*	1.91 (1.71)	1.89 (1.65)	1.25, 1.53	1.31, 1.44	0.35	0.25
	2	1.82 (1.62)	1.89 (1.71)	1.26, 1.44	1.22, 1.55	0.19	0.37
	3	1.76 (1.64)	1.91 (1.73)	1.15, 1.52	1.22, 1.57	0.19	0.33
	4*	1.90 (1.66)	1.92 (1.67)	1.32, 1.44	1.32, 1.45	0.29	0.23
	5*	1.90 (1.66)	1.77 (1.58)	1.30, 1.45	1.24, 1.42	0.33	0.20
Willstrop* (3) vs. Rodriguez (25)	1*	1.82 (1.59)	1.97 (1.73)	1.31, 1.39	1.29, 1.53	0.14	0.32
	2*	1.83 (1.60)	1.92 (1.71)	1.30, 1.40	1.26, 1.53	0.13	0.37
	3*	1.87 (1.60)	1.92 (1.71)	1.37, 1.36	1.25, 1.53	0.11	0.11
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
Ashour* (1) vs. Pilley (19)	1*	1.95 (1.57)	1.86 (1.58)	1.54, 1.27	1.39, 1.33	0.11	0.19
	2*	2.04 (1.65)	1.87 (1.69)	1.53, 1.34	1.23, 1.53	0.30	0.41
	3*	2.03 (1.70)	2.02 (1.72)	1.43, 1.42	1.38, 1.46	0.28	0.22
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
AVERAGE (standard deviation)		**1.87 (±0.07)**	**1.88 (±0.07)**	**1.40, 1.34**	**1.34, 1.40**	**0.26 (±0.12)**	**0.27 (±0.13)**

**The asterisk marks the winner of the match and which games they won in the match.*

Table 8. Mean speed, speed distribution parameters, after removing low-end speeds < 1.0 m/s.

Player (rank)	Game #	Mean Speed (standard deviation) m/s	Speed distribution parameters k, θ	% of excluded velocity data

						0 - 1.0 m/s	
		Winner	Loser	Winner	Loser	Winner	Loser
Ashour* (4) vs. El Shorbagy (3)	1*	2.47 (1.16)	2.57 (1.24)	4.58, 0.54	4.33, 0.59	29.3	29.9
	2*	2.48 (1.14)	2.50 (1.17)	4.70, 0.53	4.55, 0.55	30.1	32.4
	3	2.47 (1.16)	2.51 (1.17)	4.49, 0.55	4.62, 0.54	32.1	33.4
	4*	2.39 (1.09)	2.48 (1.15)	4.78, 0.50	4.62, 0.54	32.4	31.7
	5	\	\	\	\	\	\
El Shorbagy* (5) vs. Mustonen (53)	1	2.41 (1.08)	2.40 (1.08)	4.98, 0.48	4.96, 0.48	30.6	33.9
	2*	2.50 (1.17)	2.46 (1.12)	4.55, 0.55	4.85, 0.51	28.4	31.5
	3	2.41 (1.06)	2.38 (1.04)	5.16, 0.47	5.23, 0.46	29.4	31.5
	4*	2.41 (1.09)	2.48 (1.13)	4.86, 0.50	4.84, 0.51	31.7	30.1
	5*	2.52 (1.18)	2.51 (1.09)	4.58, 0.55	5.27, 0.48	30.9	29.5
Pilley* (18) vs. Mustonen (51)	1*	2.58 (1.24)	2.55 (1.17)	4.37, 0.59	4.72, 0.54	31.3	30.9
	2	2.53 (1.17)	2.58 (1.26)	4.73, 0.54	4.23, 0.61	33.8	31.9
	3	2.53 (1.17)	2.59 (1.24)	4.66, 0.54	4.37, 0.59	36.2	31.3
	4*	2.53 (1.18)	2.57 (1.18)	4.58, 0.55	4.73. 0.54	29.7	30.3
	5*	2.54 (1.22)	2.50 (1.15)	4.35, 0.58	4.71, 0.53	30.8	35.0
Willstrop* (3) vs. Rodriguez (25)	1*	2.48 (1.12)	2.64 (1.21)	4.90, 0.51	4.80, 0.55	32.3	30.2
	2*	2.48 (1.14)	2.65 (1.25)	4.71, 0.53	4.46, 0.59	32.0	32.6
	3*	2.52 (1.17)	2.61 (1.20)	4.68, 0.54	4.75, 0.55	31.3	31.4
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
Ashour* (1) vs. Pilley (19)	1*	2.52 (1.17)	2.51 (1.15)	4.62, 0.55	4.75, 0.53	28.4	31.5
	2*	2.60 (1.22)	2.56 (1.20)	4.56, 0.57	4.52, 0.57	26.8	32.2
	3*	2.65 (1.25)	2.65 (1.26)	4.50, 0.59	4.44, 0.60	28.9	29.1
	4	\	\	\	\	\	\
	5	\	\	\	\	\	\
AVERAGE (standard deviation)		**2.50 (±0.07)**	**2.54 (±0.08)**	**4.67, 0.54**	**4.69, 0.54**	**30.8 (±2.1)**	**31.5 (±1.5)**

**The asterisk marks the winner of the match and which games they won in the match.*

DISCUSSION

This study aimed to provide the first evaluation of elite squash players' kinematics using video analysis software. Our method was validated when compared with previous studies (Hughes and Franks, 1994; Vučković *et al.*, 2003; 2009; 2010; 2013). We believe our method possesses a superior advantage over previous live-data acquisition methods; the ability to analyze any match that has been filmed from a suitable angle (as every recent match filmed by the PSA has been filmed) opposed to requiring a special camera setup for a real-time squash tracking system. This significantly increases the sample of elite tournament games that can be analyzed. The main limitation to this method is the rate of the tracking algorithms, which can be improved in the future. This system tracks only the feet of players which eliminates any error from trunk/racquet motion that has been recorded by real-time tracking systems (Vučković *et al.*, 2010).

Of the matches analyzed, slightly less than half of match time (44.8% on average) was time when the ball was actually in play. This provides an interesting look into the physiological demands of elite squash, confirming that squash is a collection of repeated, short, high intensity bouts rather than a constant intensity endurance sport (Girard *et al.*, 2007). The sidewall and close up secondary cameras did not show both players and was deemed not useful for comparison analysis. These camera views were typically used when players were repeating shots: backhands down the wall or drop shots. The amount of movement from players during these repetitive shots is assumed to be relatively equal as the players perform similar cyclical movements between the T and the corner. The inability to analyze 100% of match play (81.2% analyzed on average) is a limitation of this study's methodology. However, the methods applied provide valid results for comparison. The results of this study align with Hughes and Franks (1994); Vučković *et al.* (2003), (2009); and Vučković and James (2010).

Specific coordinate mapping equations had to be created for each tournament since the main camera's position varied slightly. The equations were effective at predicting a player's position at any point on the court, but they were more accurate when a player was near centre court rather than the corners. This is likely because there were more available calibration points (the service lines) near centre court opposed to corners.

The mean distance travelled by winners and losers in our study (537 m and 541 m, respectively) compared to a previous study's values of 672 and 656 m, show a smaller distance covered (Vučković *et al.*, 2003). This could be due to multiple reasons: Our matches were following the point-a-rally system rather than point-a-serve used in the aforementioned studies' matches, which leads to shorter games. The differing level of playing standard in sample matches may also have an effect. This study's matches were of recent elite players (rank 1-53 in the world in years 2012-2014), whereas Vučković *et al.* (2003) used 3 matches from Slovenian National Championships and 3 matches from Austrian International Championship, both of which took place in 2001 and only featured players from Austria, Hungary, Slovenia and Bavaria (Vučković *et al.* 2003). Our study is also lacking a portion of distance travelled for both players, since not all active play was analyzed. Finally, with such large variation in distances travelled within both studies, it is difficult to assign a 'normal' distance travelled to such a highly variable sport.

Although there was a large range of distances travelled in analyzed games (338 – 982 m), players travelled similar distances in each individual game, similar to previous studies (Vučković *et al.*, 2003; Vučković and James 2010). The mean difference in distance travelled by players in a game was 3 (± 25) m. The winner travelled 3 m less on average than the loser which is only 0.6% of the average total distance travelled in a game. With the near negligible difference in average distance travelled, it appears that in elite level tournament squash there's no correlation between distance travelled and the outcome of the game. Rather, the players must play to the pace of their opponent, and distance travelled in a game is correlated with length of game and number of points scored (Vučković *et al.* 2003). A player must be capable and willing to travel up to a kilometer or more in a single game to meet one of the many physical requirements to play squash at a professional level (Albernethy, 1990; Girard *et al.*, 2007). Martínez-Gallego *et al.* (2013) found elite tennis players to travel only 82 m on average during active play in a game. This study's average distance travelled by an elite squash player is an astonishing 656% larger than the average distance travelled in an elite tennis game (Martínez-Gallego *et al.*, 2013).The large gap in distance travelled highlights the physiological differences between the two racquet sports.

Vučković *et al.* (2009) results suggest that spending more time near the T (mid-court position) indicates dominance of rally. They concluded that winners spent more time occupying the space close to the T than losers, except for closely contested games (Vučković *et al.*, 2009). This is in agreement with our study where the winner had maintained a smaller average radius to the T in 13/20 games. Higher ranked players also stayed closer to the T on average than did lower ranked players as seen in a game where El Shorbagy (rank 5) maintained an average radius of 1.53 m around the T and Mustonen (rank 53) maintained an average radius of 1.98 m around the T. This can be contrasted to a closely contested (rank-wise) match where Ashour (rank 4) played El Shorbagy (rank 3) and they attained near equal average match radii (1.73 m and 1.74 m respectively). In 14/20 games, the higher ranked player maintained a closer radius to the T, regardless of win or loss.

A strong correlation was found between PSA rank and average radial distance from the T; r = 0.64, p<0.001, 95% CI [0.0025,0.0056]. Similarly, a correlation between T radius and outcome of game was found; r = 0.33, p<0.05, 95% CI [-0.158, -0.005]. The values of the slopes for these regressions imply that higher ranked players (#1 being the best) and game winners both maintain smaller radii to the T. This is likely due to higher ranked players having increased tactics and skills. Hughes (1985) suggests that less skilled players typically play a larger share of shots into the T area (Hughes, 1985; Vučković *et al.*, 2009). More accurate shots will force the opponent to leave the T area more frequently, thus increasing their radial distance. This is also why higher ranked players were able to maintain a smaller radius when playing a lower ranked player. The lower ranked (less skilled) player will not be as effective in their shot placement skills and will play more shots back to the T, where the more skilled player is waiting. This may be in fact what sets apart players good enough to be ranked top 5 in the world: their ability to dominate the court and control the all-important T, while forcing their opponent out of it.

The simple analysis of percent of active match play spent left/right/in front/behind the T yielded interesting results. In only 1 game did both players play to the right hand side more frequently than the left. (Note that all players in analyzed games were right handed). On average, players spent 57.3% of the game left of the T. In reality, it is likely that this percentage is even higher since the left side wall camera view was not analyzed. This camera was only used when one (but often both) of the players were receiving a shot down the left hand wall. There was no secondary camera for the right side wall. This higher percentage spent on the left (backhand) side was expected, at least at the elite level, where players are using a suspected tactic to play to their opponent's backhand (which is traditionally considered more difficult for all players). Putting an opponent to their backhand wears down their weaker shot and increases the chance of forcing a mistake. This conclusion aligns with the results of Vučković *et al.* (2013) where they concluded in 64.6% of shots came from the left hand side of the court.

As for percent of time spent in front and behind the T, players spent an overwhelming 89.3% of time behind the T. This reported percentage is likely higher than in reality. This is because the front wall close up camera view was not analyzed. This camera view was only used when a drop shot (or similar short range shot) was performed that put both players in front of the T. This conclusion aligns with the results of Vučković *et al.* (2013) which found 74.4% of shots came from behind the T. There was no significant difference (<2%) between the percent winners and losers spent on average left or behind the T. Plotting the players' radius to the T against time shows the sinusoidal nature of the players' radius to the T as the rally progresses. One player will reach a maximum distance while the other reaches a minimum, as seen in (Figure 1). This reflects the general nature of squash play where one player will have to leave the ideal T position to return the ball, as the other player moves back toward the T to prepare for their opponent's shot.

Since the time played for both players is the same, the player who covers more ground in a game will have a higher average speed. This can be seen in a sample game where El Shorbagy travelled 20 m farther and had an average speed 0.06 m/s faster than Ashour. The maximum recorded average speed was 2.04 m/s, which is very similar to Hughes and Franks (1994) maximum mean speed of 1.98 m/s. While there are short lasting, intense bouts of sprinting, the average speed maintained throughout analyzed match play for all players was 1.88 m/s. This average speed represents a minimum threshold that a player must be physically capable of maintaining for the duration of a game. Studies have shown the average walking speed of humans is around 1.4 m/s while the preferred walk-to-run transition speed occurs just below 2 m/s (Mohler *et al.*, 2007; Raynor *et al.*, 2002; Kram *et al.*, 1997). Motion in squash is comprised of continuous transitions between walking and running, with many changes of direction and lunges. This is reflected in our average speed of 1.88 m/s, which lies just below this transition speed. While this speed would seem slow for someone moving in a straight line, the majority of energy expenditure in squash likely comes from rapid changes in direction. Martínez-Gallego *et al.* (2013) found elite tennis players to move with an average speed of 1.36 m/s, which is 38.2% slower than the average speed of elite squash players in this study. Based on player speed alone, it would appear squash is more physically intensive, and certainly a faster moving sport than tennis (Martínez-Gallego *et al.*, 2013).

Creating frequency distributions of speeds that players acquired provided a graphical view of how often players spend at the largely varying speeds achieved in professional squash. It was then noticed that 31.2 ($\pm$ 1.8) % of time when the ball was in play, players were still only moving at speeds that are considered slow (<1.0 m/s), with no significant difference between winners and losers. The speeds that fall within the < 1.0 m/s range are associated with the low speeds of a player when: they are awaiting their opponent's shot from a neutral centre court position, they are making a shot and momentarily pause to get an accurate and powerful shot, or the players switch directions. We propose that removing these low end speeds provides a more realistic average speed of a player moving to return a shot. With this exclusion, the mean speed of players becomes 2.52 m/s. This was an interesting observation as this means only 69.6% of active match play has players moving $\geq$1 m/s and only 31.2% of a full match is spent moving ≥1 m/s! While squash is no doubt incredibly taxing on the cardiovascular system, at the elite level (top 50 in the world) it is likely that the players already have an adequate level of conditioning and endurance capabilities that allow them to compete at that level. Winning or losing is then determined by a variety of other factors including tactics, skills, and mental capabilities. This may have an influence on training elite players with programmes that emphasize these qualities, with less effort spent on development of aerobic capacity (Vučković and James, 2010).

One limitation of our study is the lack of analysis of the accuracy of the developed method of converting the video coordinates into court coordinates. In particular, our method assumes that the players' feet are sliding along the plane of the court and so the actual vertical movement of the players during jumping would be considered as distance travelled. However, the method perhaps slightly overestimates the distance travelled and the velocities albeit equally for both players. In addition, the method does not take into consideration any lens warping. Our future work will focus on developing and experimentally testing the reliability of this method.

CONCLUSIONS

With the increasing availability and technological improvements of motion tracking software, this study sought to provide quantification of elite squash kinematics and tactics using video analysis techniques. Not only was the methodology applied proven to be accurate and reliable when compared to previous studies methods, but is believed to be more effective by removing the limitation of live data acquisition. Distance travelled, position relative to the T, dominance of the T, average velocities, frequency distribution of velocities, and approximate rallies in a game were all quantified. The results further concluded that distance travelled and average velocity of a player has no indication to the outcome of the game, or rank of player. It is suggested that further studies investigate average velocities corresponding to players moving away from the T, as this may be a more appropriate measure of player's velocity when they are intending to move quickly.

The T of the squash court is commonly believed by players and coaches to be a position of control on the court. Measuring the average radial distance from the T of players allowed us to quantify this claim. A strong correlation between PSA world ranking and average game radius was found; r = 0.64, p<0.001, 95% CI [0.0025,0.0056]. It appears at the elite level, a squash player's rank is indicative of their ability to control the T and dominate the court.

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