©Journal of Sports Science and Medicine (2022) **21**, 82-90
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2022.82

Research article

Physiological and Performance Correlates of Squash Physical Performance

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Abstract

The physiological and performance attributes of elite squash players were investigated. Thirty-one players (21 males, world ranking [WR] 42-594; 10 females, WR 7-182) completed a battery of fitness tests which included an aerobic squash-specific physical performance test (SPPT), repeated-sprint ability (RSA), change-of-direction speed (COD), acceleration (5-m sprint), body composition and force development (countermovement jump) assessments. The SPPT provided a finishing lap score, $\dot{V}O_{2max}$, average movement economy and the lap corresponding to a blood lactate concentration of 4 $mM{\cdot}L^{-1}$. Players were ranked and assigned to HIGH or LOW performance tiers. Two-way ANOVA (performance level*sex) revealed higher ranked players performed better ($p < 0.05$) for SPPT final lap ($d = 0.35$), 4 $mM{\cdot}L^{-1}$ lap ($d = 0.52$) and COD ($d = 0.60$). SPPT displayed a 'very-large' correlation with 4 $mM{\cdot}L^{-1}$ lap ($r = 0.86$), 'large' correlations with COD ($r = 0.79$), RSA ($r = 0.79$), sum-of-7 skinfolds ($r = 0.71$) and $\dot{V}O_{2max}$ ($r = 0.69$), and a 'trivial' correlation with average movement economy ($r = 0.02$). Assessments of cardiovascular fitness (i.e. 4 $mM{\cdot}L^{-1}$ lap), RSA, COD and body composition appear highly pertinent for performance profiling of squash players. Regular, submaximal assessment of the 4 $mM{\cdot}L^{-1}$ lap during the SPPT may offer a practical athlete monitoring approach for elite squash players.

Key words: Squash, fitness testing, aerobic fitness, sport-specific, squash training.

Introduction

Elite squash players are characterised by their ability to undertake repeated high intensity movements (accelerations, decelerations and changes of direction) over short distances (3-6 m), throughout rallies lasting 15-30 s (Girard and Millet, 2009). Elite players may possess aerobic capacities exceeding 50 and 60 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ in females and males, respectively (Girard et al., 2005; Gouttebarge et al., 2013), as well as ventilatory thresholds (i.e. VT^1) and respiratory compensation points (i.e. VT^2) around 84% and 90% of $\dot{V}O_{2max}$, respectively (Girard et al., 2005). Match duration ranges from 37 - 89 min (Jones et al., 2018) and elicits a mean intensity between 81 ± 6% (James et al., 2021a) and 92 ± 3 % (Girard et al., 2007) of maximum heart rate (HR_{max}), with variability in this response most likely due to unequal matching of playing abilities (Murray et al., 2016). Matches involve noteworthy contributions from both aerobic and anaerobic energy systems, with 25% of playing time exceeding 90% of $\dot{V}O_{2max}$ and the mean blood lactate concentration above 8 $mM{\cdot}L^{-1}$ (Girard et al., 2007). Accordingly, elite players display considerable training volumes (James et al., 2021b) and the assessment and training of both aerobic and anaerobic energy systems is highly pertinent (Jones et al., 2018).

To maximise the ecological validity of fitness assessments, tests should reflect the specific demands of the sport (Wilkinson et al., 2009a). Therefore in squash, on-court assessments of change-of-direction speed (COD) (Wilkinson et al., 2009b), repeated-sprint ability (RSA) (Willkinson et al., 2010) and aerobic fitness (Girard et al., 2005; Wilkinson et al., 2009c; Gouttebarge et al., 2013; James et al., 2019) are more appropriate, than generic assessments. Wilkinson et al. (2012) investigated the physiological characteristics and performance attributes that correlated with RSA performance in a group of junior and senior elite players. The authors identified world rank to be correlated with both RSA and COD performance (Wilkinson et al., 2012). While strong positive correlations were identified between RSA and COD for both male ($r = 0.90$) and female ($r = 0.84$) players, a significant correlation was only reported between reactive strength and RSA in male players ($r = 0.71$) (Wilkinson et al., 2012). Therefore, whilst both male and female players demonstrate the ability to sustain frequent and rapid changes of direction (Wilkinson et al., 2012), females may require different physical benchmarking to males, for accurate training prescription. An RSA test was used to reflect the high intensity nature of elite matchplay and appears pertinent as elite squash players exhibit larger speeds and accelerations than sub-elite players (Hughes and Franks, 1994). However, as matchplay often exceeds 60 min and elite players appear to possess both considerable $\dot{V}O_{2max}$ values (Jones et al., 2018) and ventilatory thresholds (Girard et al., 2005), physical performance on aerobic tests should also be considered.

Previously, neither Girard et al. (2005), nor Wilkinson et al (2012) identified significant relationships between world ranking (WR) and $\dot{V}O_{2max}$ measured during treadmill or 20 m shuttle run tests, respectively. However, as squash-specific on-court fitness tests appear necessary to differentiate higher and lower standard players (Steininger and Wodick, 1987; Girard et al., 2005), these findings may reflect a lack of specificity in the chosen aerobic tests. We have recently demonstrated a squash physical performance test (SPPT), as an on-court, multi-direction, intermittent running test, yielding valid $\dot{V}O_{2max}$ and metabolic threshold measurements when compared to a traditional treadmill protocol, in elite male and female squash players (James et al., 2019). However, it remains unclear whether SPPT performance measures (final lap or the lap corresponding to a blood lactate concentration of 4 $mM{\cdot}L^{-1}$) alone, can differentiate higher and lower ranked players

Received: 08 June 2021 / Accepted: 23 December 2021 / Published (online): 10 January 2022

within an elite cohort. The assessment of on-court sub-maximal oxygen consumption may also be beneficial as it provides an integrated, squash-specific assessment of oxygen kinetics and movement economy (James et al., 2019), which are consistently challenged during the intermittent profile of match play. Despite sport-specific assessments of movement economy being conducted in other intermittent team sports (Dolci et al., 2018), this has yet to be investigated in squash.

Squash-specific assessments appear necessary to examine the importance of aerobic fitness parameters for elite squash players (Wilkinson et al., 2012), as they provide an integrated evaluation of pertinent fitness components. In turn, this may improve the specificity of physical profiling within squash, facilitating more effective individual training prescription and/or talent identification (Wilkinson et al., 2012). Therefore, the aims of this study were to; (1) determine whether the SPPT performance, both final lap and the lap associated with a blood lactate concentration of 4 $mM{\cdot}L^{-1}$, can differentiate between higher and lower ranked elite squash players and, (2) explore the relationships between various physiological and performance outcomes with SPPT performance.

Methods

Experimental design

Data were derived from quarterly fitness testing at the National Squash Centre of Malaysia. Testing occurred on multiple occasions over 18-months, always commencing on a Monday morning, following 36 - 48 hours rest and under consistent environmental conditions (25.7 ± 1.9 °C, 56 ± 5.8 % relative humidity). Players completed individual warm-ups, which were replicated for all testing sessions. Warm-ups included jogging, lateral movements, accelerations and mobility exercises. Players then completed the SPPT, followed by a 5 - 10 min low intensity warm-down and individual stretching. Players rested on Monday afternoon and returned the following morning for further assessments. On the second day, players warmed-up and completed the following assessments in a fixed order; (i) 5 m sprint, (ii) COD and (iii) RSA. Body composition and jump tests were conducted within 7 days of these tests, following 24 hours rest. Body composition was measured during a morning, prior to any training. All players were familiarised with testing protocols, having completed all tests on at least two prior occasions. Approximately three months after completing the testing battery, a subset of players completed a second SPPT using a portable metabolic cart, to assess cardiorespiratory responses. For all analyses, the SPPT score was used as a measure of squash physical performance.

Participants

Thirty-one professional Malaysian squash players volunteered for this study. The cohort comprised 21 males (age 20 ± 4 years, body mass 65.0 ± 6.0 kg, stature 172.8 ± 6.4 cm, sum of 7 skinfolds 53.1 ± 16.5 mm, WR 42-594) and 10 females (age 18 ± 5 years, body mass 55.7 ± 5.0 kg, stature 1.60 ± 0.04 m, sum of 7 skinfolds; 94.7 ± 22.2 mm, world ranking 7 - 182). This cohort encompassed all national players based full-time at the squash centre of Malaysia and enabled a large effect size (when greater than ≥0.53) to be identified between higher and lower performance groups for SPPT performance. This sample size will detect a difference at $p < 0.05$, with a power of 80%. The power calculation was carried out using *Gpower* software (v.3.1.9.3 Bonn University, Germany). Of the original cohort, fifteen players completed a second SPPT test to investigate cardiorespiratory responses (11 male, 22.1 ± 4.5 years, WR 42-386 and 4 females, 22.8 ± 7.8 years, WR 7-76).

All players typically completed ten training sessions per week (~12 hours), had resided at the national high-performance centre of Malaysia for at least 1 year and regularly competed in international Professional Squash Association (PSA) events. A typical training week comprised three 'group' on-court training sessions, one/two match-play sessions, one/two individual coaching 'feeding' sessions, two strength sessions and two/three conditioning sessions (James, et al., 2021b). All players provided written, informed consent and the study received institutional ethical approval from *Institut Sukan Negara*, conforming to the Declaration of Helsinki.

Player ranking and performance level assignment

To investigate differences between higher and lower performing players on the SPPT, two national coaches independently assigned all players a numerical rank, with males (n = 21) and females (n = 10) ranked separately. Mean 'coach' ranking was used to order players, and where this did not differentiate players (n = 4 instances), the most recent match result determined the relative position. A coach ranking approach was utilized as four players did not have a current WR, and this helped mitigate any legacy effects of the rolling average calculation of a player's current world ranking, which may not be reflective of a player's physical status at a given time. For example, if injury had previously enforced a break from tournament participation. Of players who had a current WR (obtained from the PSA website), there was strong agreement between WR at the time of fitness assessments and the 'coach' ranking for both males ($r_s = 0.998$, $p = 0.001$, n = 18) and females ($r_s = 0.800$, $p = 0.005$, n = 9). Players were assigned to performance levels (HIGH or LOW) based on their coach ranking, with the top half of males and females assigned to HIGH and the bottom half assigned to LOW.

Procedures

Squash physical performance test

A schematic of the SPPT, as well as data concerning the reliability and validity of physiological measurements, can be found in James et al. (2019). Briefly, players undertook repeated, multi-directional shuttle runs on the squash court, in accordance with audio beeps, until volitional exhaustion. Reflecting the intermittent nature of squash, players rested for 10 s after each lap and 30 s between stages. Each stage lasted between 3 - 4 min and speed increased by 0.19 $m.s^{-1}$ between stages. After every stage, fingertip capillary blood samples were collected (Lactate Scout, EKF Diagnostics, UK). The lap number corresponding to 4 $mM.L^{-1}$ was calculated from the polynomial regression equation for blood lactate concentration versus lap number, providing a measure of the lactate turn-point (James et al., 2017a). This measure has been shown to display a typical error of 4 laps (7%) (James et al., 2019). The test ended when the participant failed to reach the 'T' at the required time for two consecutive laps (>1 m short), with the last successfully completed lap number recorded as the player's score (SPPT Final Lap, typical error 3 laps [4%]).

Metabolic measurements

When cardiorespiratory measures were recorded during the second SPPT, players wore a portable metabolic cart (Cosmed K5, Rome, Italy). Before every test, the metabolic cart was calibrated in accordance with manufacturer's instructions. The mean submaximal oxygen consumption ($mL\cdot kg^{-1}\cdot km^{-1}$) during the final minute of first four stages of the test were averaged as a measure of movement economy (James et al., 2017a). The typical error of this measure was 0.94 $mL\cdot kg^{-1}\cdot min^{-1}$ (2.5%), (James et al., 2019).$\dot{V}O_{2max}$ was taken as the highest moving 10 s average observed during the test (typical error = 1.5 $mL\cdot kg^{-1}\cdot min^{-1}$ [3.2%]), (James et al., 2019).

5m sprint test

Players completed three 5m sprints on a squash court, each separated by 3-min rest. Each sprint started from a standing position, 1m behind the designated starting line. Sprint duration was measured using electronic timing gates (Smartspeed, Fusion Sport, Brisbane, Australia), with the fastest time used for analysis.

Change-of-direction speed test

Following a 5-min rest, players completed a squash-specific COD test. A test schematic, as well as the reporting of both validity and reliability (0.13 s / 1.2%) are described by Wilkinson et al. (2009b). Players completed three trials of the course, with 3-min rest between efforts. The fastest time was used for analysis. Players were instructed to complete the course as quickly as possible, but no instruction was provided around technique.

Repeated-sprint ability test

Following a further 5-min rest, players completed a squash-specific RSA test (Willkinson et al., 2010). This uses the same layout as COD, but requires two laps of the course for each repetition. Only one attempt of the test was undertaken, which involves a total of ten repetitions, each separated by 20 s rest. The total time to complete ten repetitions was recorded and a fatigue index (FI) calculated in accordance with Glaister et al. (2008). This divided the total time by the ideal time, providing a percentage reduction. Ideal time was calculated by multiplying the total number of sprints by the fastest single repetition. Validity and reproducibility of the test are detailed within Wilkinson et al. (2010), but in brief, typical error of the total time for 10 sprints was 6 seconds (2.2%).

Anthropometric profiling

Eleven measurements were taken from each player. These included stature (m), body mass (kg), sum of seven skinfolds (mm) and two girth measurements. The seven skinfolds were biceps, triceps, sub-scapular, suprailiac, mid-thigh, proximal calf and medial calf. All skinfolds were taken using Harpendon calipers (British Indicators Ltd., UK) by the same, trained practitioner (ISAK level 2). Mid-thigh and maximum calf girths were measured using a tape measure (Lufkin W606PD, USA).

Squat jumps and countermovement jumps

Squat jump (SJ) and countermovement jump (CMJ) assessments were conducted using a contact mat (SmartJump, Fusion Sport), following a warm-up. This contained mobility exercises, light jogging and progressively more forceful submaximal jumping and hopping. Players completed three trials of both jumps, with 1-min rest between. Ten minutes rest was allowed between SJ and CMJ. The highest jump was recorded as the score. Jump height was estimated from flight time using the formula: Jump Height = 9.81 * (flight time)^2 / 8. For both jumps, players were required to maintain their hands on their hips, feet shoulder-width apart, to straighten legs in mid-air, and to land with soft knees. For SJ, players assumed a semi-squat position at 90° of knee flexion and held this position for two seconds before jumping without any pre-stretch movement. CMJs were completed with a counter movement immediately preceding take-off. Jumps were completed by 13 players; six players were unable to participate due to other training requirements. Depth was not controlled for CMJs, however all players were familiarised with this protocol, having completed it on multiple previous occasions.

Statistical analyses

World ranking data are reported as median (interquartile range). Remaining data are reported as mean (±SD) and were analysed using SPSS software (V25, SPSS Inc, Chicago, USA). Differences were considered significant when $p < 0.05$. Data were checked for normality of distribution and homogeneity of variance, using the Kolmogorov-Smirnov and Levene's tests, respectively. Physiological and performance data were analysed using two-way ANOVA, to explore the effect of Performance Level (HIGH / LOW) and Sex (male / female) on SPPT final lap and the lap associated with 4 $mM.L^{-1}$. Significant findings were followed up with pairwise comparisons, using a Bonferroni correction. Cohen's d effect sizes are presented. Pearson's Product Moment Correlation coefficient (r) was calculated separately for males and females between outcome variables and the SPPT scores. Correlational analysis was also performed on the pooled data to increase the generalisability of our findings across a range of squash performance levels. Where a player did not undertake all assessments, existing data was retained for analysis, with total samples displayed in Tables 2 and 3. For metabolic and hematological data arising from the second SPPT (n = 15), correlations were only calculated from the pooled data due to the smaller sample size. In the absence of field specific estimates, Pearson's r was interpreted using guidelines from Cohen; <0.1 trivial, 0.1 - 0.29 small, 0.3 - 0.49 moderate, 0.50 - 0.69 large (Cohen, 1988), with large correlations further differentiated into 0.70 - 0.89 very large and 0.90 - 0.99 nearly perfect (Hopkins et al., 2009). Subsequently, linear regression analysis was conducted to investigate the ability of each fitness parameter to predict SPPT performance, for both males and females. Prior to regression analysis, data were further checked for independence of observations, using the Durbin-Watson statistic.

Results

The HIGH and LOW performance levels for males, displayed a WR range of 42 - 278 (mean 146, median 121, interquartile range 64 - 229) and 310 - 594 (mean 435, median 385, interquartile range 361 - 526), respectively. For females, the HIGH WR range was 7 - 101 (mean 63, median 64, interquartile range 47 - 93) and 103-182 (mean 132, median 110, interquartile range 107 - 146) for LOW.

SPPT Performance

There were statistically significant main effects of Performance Level ($F = 4.331$, $p = 0.047$, $d = 0.35$) and Sex ($F = 23.004$, $p < 0.001$, $d = 1.82$) on SPPT final lap performance. Participants in HIGH outperformed LOW (79.2 ± 10.0 vs 74.9 ± 14.7 laps), while males completed more laps than females (82.6 ± 9.4 vs 65.6 ± 10.4 laps).

There were statistically significant main effects of Performance Level ($F = 4.707$, $p = 0.04$, $d = 0.52$) and Sex ($F = 18.644$, $p < 0.001$, $d = 1.67$) on 4 $mM{\cdot}L^{-1}$ lap performance. Participants in HIGH completed more laps before achieving a blood lactate of 4 $mM{\cdot}L^{-1}$ compared to LOW (61.8 ± 10.3 vs 56.5 ± 10.5 laps), while males outperformed females (64.1 ± 7.7 vs 50.5 ± 9.7 laps). Descriptive statistics for all variables, are shown in Table 1.

Performance and physiological determinants

Correlations between physiological and performance attributes and SPPT performance are shown in Tables 2 and 3. SPPT final lap performance was significantly correlated with 4 $mM{\cdot}L^{-1}$ lap, COD, and RSA for both males and females (Table 2 and Figure 1). Pooled data revealed significant correlations between SPPT final lap and 4 $mM{\cdot}L^{-1}$ lap, 5 m sprint time, COD, RSA, RSA FI, sum of 7 skinfolds, SJ and CMJ. In addition to Final Lap, 4 $mM{\cdot}L^{-1}$ lap performance was significantly correlated with RSA for males, with a non-significant relationship between 4 $mM{\cdot}L^{-1}$ lap and RSA ($p = 0.06$) for females (Table 3). Pooled data revealed significant correlations between 4 $mM{\cdot}L^{-1}$ lap and 5 m sprint time, COD, RSA, and sum of 7 skinfolds.

SPPT final lap (77 ± 9 laps) was significantly correlated with $\dot{V}O_{2max}$ (47.7 ± 5.3 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, $r = 0.686$, $p = 0.005$, $n = 15$), and 4 $mM{\cdot}L^{-1}$ (62 ± 5 laps, $r = 0.837$, $p = 0.001$, $n = 15$), but not average movement economy across the first four stages (263.6 ± 5.3 $mL{\cdot}kg^{-1}{\cdot}km^{-1}$, $r = 0.019$, $p = 0.946$, $n = 15$). There was a large correlation between 4 $mM{\cdot}L^{-1}$ and $\dot{V}O_{2max}$ ($r = 0.579$, $p = 0.024$, $n = 15$), but not with average movement economy ($r = 0.009$, $p = 0.975$, $n = 15$). Based upon these data, a diagram of training priorities for Squash players is presented in Figure 2.

Discussion

This study investigated whether the SPPT could differentiate between higher and lower ranked players, as well as the physiological and performance correlates of SPPT performance. The SPPT demonstrates construct validity, as it discriminated between HIGH and LOW ranked players across final lap ($d = 0.35$) and 4 $mM{\cdot}L^{-1}$ lap ($d = 0.52$). These results highlight the importance of using sport-specific aerobic performance measures to profile elite male and female squash players, across junior and senior levels. Secondly, we investigated physiological and performance determinants of SPPT final lap and found large - very-large correlations ($r = 0.68$-0.86) with 4 $mM{\cdot}L^{-1}$ lap, RSA, COD, body composition and $\dot{V}O_{2max}$.

Table 1. Mean ± SD (top row, shaded), median and range (bottom row, unshaded) of measured variables, displayed by sex and performance level. P values for pairwise comparisons are displayed with Cohen's *d* effect size, and 95% confidence intervals of effect size below in brackets.

Outcome variable	Male	Female	Outcome	LOW	HIGH	Outcome
Final Lap	82.6 ± 9.4	65.6 ± 10.4	*p = .001, d = 1.82	74.9 ± 14.7	79.2 ± 10.0	*p = .047, d = .35
	(84, 58 - 94)	(64, 51 - 84)	(.93, 2.7)	(76, 51 - 94)	(78, 60 - 93)	(-.36, 1.06)
4 $mM{\cdot}L^{-1}$ Lap	64.1 ± 7.7	50.5 ± 9.7	*p = .001, d = 1.67	56.5 ± 10.5	61.8 ± 10.3	*p = .04, d = .52
	(65, 45.6 - 82)	(47.6, 40 - 67)	(.79, 2.56)	(60, 40 - 69.2)	(65, 41 - 82)	(-.22, 1.27)
5 m Sprint (s)	0.93 ± .06	1.02 ± 0.03	*p = .001, d = 1.80	.97 ± .06	.95 ± .07	p = .39, d = .21
	(.93, .82 – 1.03)	(1.01, 0.99 - 1.07)	(.88, 2.72)	(.96, .89 - 1.07)	(.97, .82 - 1.06)	(-.52, .94)
COD (s)	9.21 ± .57	10.46 ± 0.68	*p = .001, d = 2.13	9.83 ± 0.84	9.36 ± .79	*p = .028, d = .60
	(9.24, 8.23 - 10.05)	(10.32, 9.38 - 11.20)	(1.16, 3.11)	(9.85, 8.67 - 11.20)	(9.39, 8.23 - 11.05)	(-.15, 1.34)
RSA total time (s)	221.0 ± 11.0	250.6 ± 12.6	*p = .001, d = 2.69	231.2 ± 18.9	229.1 ± 17.4	p = .287, d = .12
	(223, 199 - 241)	(252, 235 - 270)	(1.63, 3.76)	(230, 199 - 270)	(226, 207 - 262)	(-.61, .85)
RSA Fatigue Index (%)	4.2 ± 1.7	5.7 ± 2.2	p = .730, d = 1.04	4.5 ± 1.5	4.9 ± 2.3	p = .975, d = .00
	(4, 1.3 - 7.3)	(6, 2 - 8.2)	(0, 1.63)	(5, 2.4 – 8.0)	(5, 1.3 - 8.2)	(-.56, .9)
Sum of 7 skinfolds (mm)	53.1 ± 16.5	94.7 ± 22.2	*p = .001, d = 2.35	66.0 ± 28.5	66.1 ± 25.5	p = .67, d = .00
	(48, 30.8 - 99.4)	(106.7, 55.4 - 116.5)	(1.34, 3.35)	(60.6, 30.8 - 116.5)	(59.8, 39.1 - 110.1)	(-.73, .73)
Calf girth (cm)	36.5 ± 2.0	34.9 ± 1.0	p = .059, d = .92	36.1 ± 2.2	35.9 ± 1.7	p = .626, d = .14
	(36.1, 34.4 - 40.7)	(34.9, 33.5 - 36.4)	(1.73, 3.91)	(35.2, 33.5 - 40.1)	(35.7, 33.9 - 40.7)	(-.73, 1.01)
Thigh girth (cm)	53.7 ± 2.6	52.3 ± 2.2	p = .186, d = .60	52.5 ± 3.2	53.7 ± 2.0	p = .057, d = .51
	(53.7, 50.2 - 59.6)	(51.9, 49.1 - 54.9)	(-.49, 1.09)	(51.4, 50.2 - 59.6)	(54.0, 49.1 - 56.6)	(-.38, 1.39)
Squat jump (cm)	37.1 ± 7.2	32.6 ± 3.7	p = .175, d = .92	33.7 ± 6.8	37.1 ± 6.3	p = .145, d = .60
	(34.7, 27.1 - 47.6)	(32.2, 28.3 - 37.5)	(-.02, 1.86)	(31.7, 27.1 - 46.9)	(35.8, 27.3 - 47.6)	(-.37, 1.49)
Countermovement jump (cm)	40.2 ± 8.1	36.7 ± 5	p = .346, d = .60	37.5 ± 7.9	40.3 ± 7	p = .145, d = .40
	(41.7, 30.2 - 52.6)	(37.4, 31.1 - 41.7)	(-.32, 1.52)	(33.6, 30.9 - 52.6)	(41.3, 30.2 - 51.5)	(-.53, 1.31)

*represents $p \leq 0.05$. 'LOW' represents players within lower half of rankings, 'HIGH' represents players in higher half of rankings.

Table 2. Physiological and performance correlates of Squash Physical Performance Test (Final Lap) for male, female and all players.

		4 mM·L^{-1} Lap	5 m Sprint Time	COD Time	RSA Total Time	RSA Fatigue Index	Sum of 7 Skinfolds	Calf Girth	Thigh Girth	Squat Jump	Counter-movement Jump
Male	R vs Final Lap	.63**	-.09	-.47*	-.44*	-.17	-.42	-.40	-.18	.30	.33
	95% CI of R	(±.30)	(±.44)	(±0.36)	(±0.37)	(±.43)	(±.38)	(±.45)	(±.5)	(±.52)	(±.51)
	n	19	20	20	20	20	20	15	15	13	13
Female	R vs Final Lap	.92**	.16	-.82**	-.76**	-.32	-.41	.39	.13	.40	.41
	95% CI of R	(±.15)	(±.66)	(±.31)	(±.39)	(±.62)	(±.6)	(±.7)	(±.75)	(±.76)	(±.76)
	n	10	9	9	9	9	9	7	7	6	6
All	R vs Final Lap	.86**	-0.48**	-.79**	-.79**	-.39*	-.71**	.06	.09	.44*	.40*
	95% CI of R	(±.11)	(±.29)	(±.15)	(±.15)	(±.32)	(±.19)	(±.42)	(±.42)	(±.38)	(±.39)
	n	29	29	29	29	29	29	22	22	19	19

*represents correlation of $p \leq 0.05$, ** represents correlation of $p \leq 0.001$. CI = Confidence intervals.

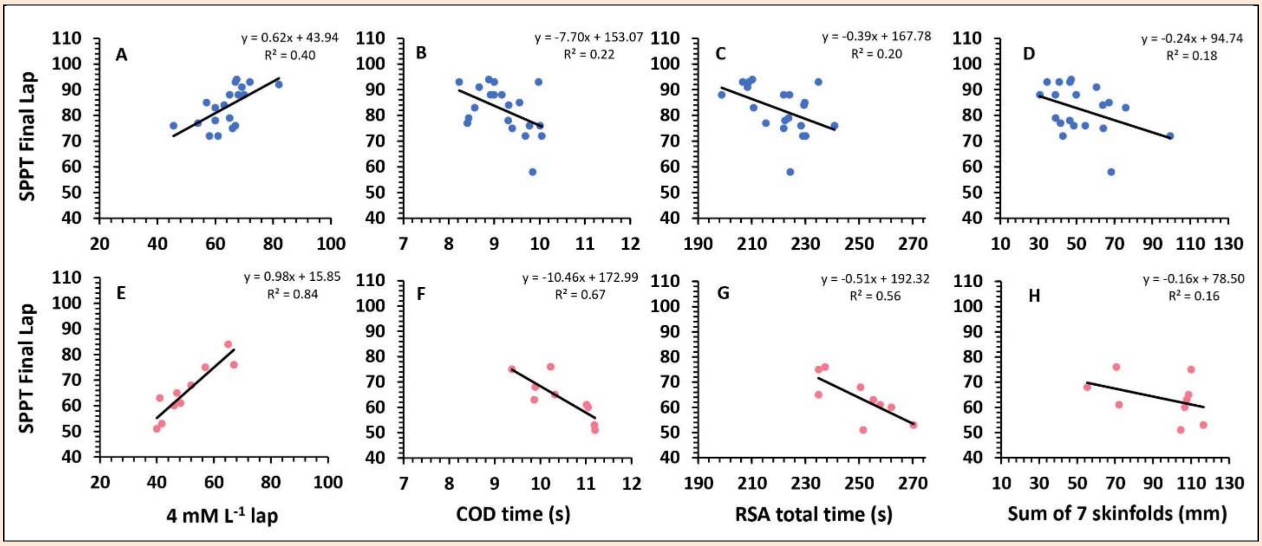

Figure 1. Linear regression plots of the relationship selected fitness variables and squash physical performance (SPPT) for males (panels A-D, blue dots) and females (panels E-H, red dots). 4 mM·L^{-1} lap = lap corresponding to blood lactate concentration of 4 mM·L^{-1}, RSA = repeated-sprint ability total time, COD = change-of-direction speed.

Table 3. Physiological and performance correlates of Squash Physical Performance Test (4 mM·L^{-1}) for male, female and all players.

		Final Lap	5 m Sprint Time	COD Time	RSA Total Time	RSA Fatigue Index	Sum of 7 Skinfolds	Calf Girth	Thigh Girth	Squat Jump	Counter-movement Jump
Male	R vs 4 mM·L^{-1} Lap	.63**	-.33	-.37	-.54*	.30	-.20	-.12	-.12	-.25	-.35
	95% CI of R	(±.3)	(±.43)	(±.42)	(±.35)	(±.43)	(±.45)	(±.53)	(±.53)	(±.55)	(±.52)
	n	19	18	18	18	18	18	14	14	12	12
Female	R vs 4 mM·L^{-1} Lap	.92**	.36	-.50	-.65#	-.57	-.53	.00	-.14	.35	.18
	95% CI of R	(±.15)	(±.61)	(±.56)	(±.47)	(±.52)	(±.55)	(±.75)	(±.75)	(±.77)	(±.8)
	n	10	9	9	9	9	9	7	7	6	6
All	R vs 4 mM·L^{-1} Lap	.86**	-.55**	-.72**	-.81**	-.32	-.68**	.22	.13	.23	.12
	95% CI of R	(±.11)	(±.28)	(±.2)	(±.15)	(±.35)	(±.22)	(±.41)	(±.43)	(±.45)	(±.46)
	n	29	27	27	27	27	27	21	21	18	18

represents correlation of $p = 0.06$, *represents correlation of $p \leq 0.05$, ** represents correlation of $p \leq 0.001$. CI = Confidence intervals.

SPPT performance

This investigation corroborates previous research illustrating that higher ranked players outperform their lower ranked counterparts when squash-specific aerobic fitness assessments are used (Steininger and Wodick, 1987; Girard et al., 2005). However, the test protocols utilized in previous research (Steininger and Wodick, 1987; Girard et al., 2005) are not directly comparable, requiring specialised computer software and equipment, as well as requiring participants to perform racquet strokes. Comparatively, the SPTT is a simple, sport-specific, graded exercise test that challenges aerobic metabolic pathways (James et al., 2019). The SPPT final lap appears to be a suitable, objective measure which contains construct validity, differentiating HIGH and LOW ranked players. Given the intermittent profile and the numerous directional changes at maximal intensity, the final lap of the SPPT is likely a composite velocity associated with metabolic factors and neuromuscular properties that enable repeated accelerations, decelerations and changes of direction (Girard et al., 2010). Therefore, the final lap score is not exclusively related to aerobic fitness qualities, as is common in laboratory protocols that demonstrate efficacy for predicting endurance performance (Noakes et al., 1990), as well as field tests for other intermittent sports (Bangsbo et al., 2008; Buchheit, 2008), making the SPPT an appropriate sport-specific assessment in squash.

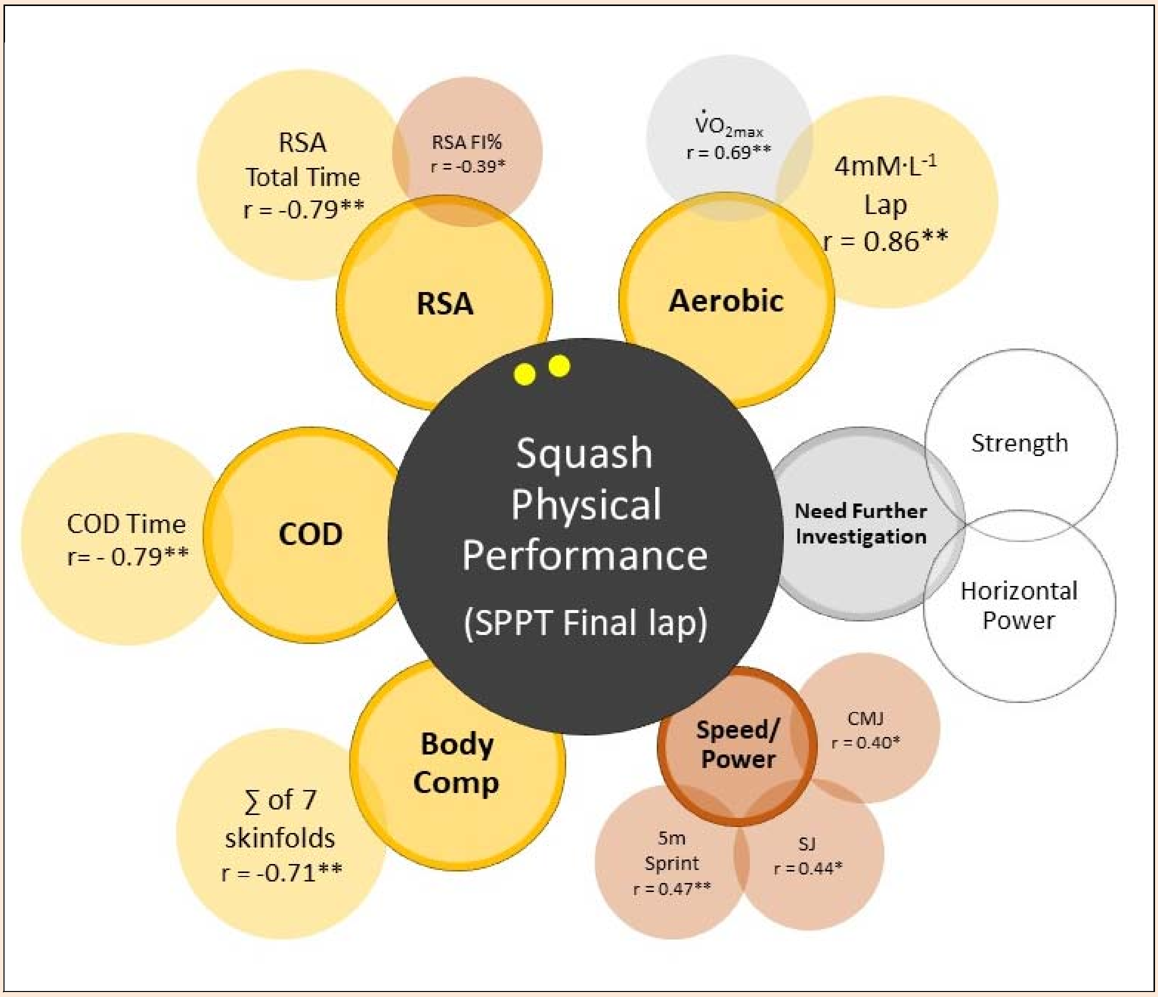

Figure 2. Gold, silver and bronze training priorities for squash performance profiling. Colours denote strength of correlation from entire testing cohort between fitness parameters and the Squash Physical Performance Test (SPPT) Final Lap (Gold = 'Very-large' (r = 0.89–0.70), silver = 'large' (r = 0.69-0.50), Bronze = 'moderate' (r = 0.49 – 0.30). RSA = repeated-sprint ability total time, FI% = RSA fatigue index, COD = change-of-direction speed, SJ = squat jump, CMJ = countermovement jump, Body Comp = body composition. *represents correlation of $p \leq 0.05$, ** represents correlation of $p \leq 0.01$.

Although this investigation reinforces the importance of aerobic conditioning within squash, the novel finding of this study is that higher ranked players possess greater submaximal aerobic fitness qualities than lower ranked players, when assessed on a squash-specific test. As match intensities commonly exceeds the second ventilatory threshold (Girard et al., 2007), this physiological attribute thereby enables higher ranked players to work at a higher intensity before fatigue-inducing metabolites begin to accumulate in the body. The test structure of the SPPT (i.e. longer stages and rest durations) allowed for blood lactate sampling, providing a practical alternative to cardio-respiratory gas analysis that may be required during other squash-specific protocols (Girard et al., 2005) for a similar submaximal assessment.

Performance Determinants

Our investigation revealed that SPPT final lap was significantly correlated with 4 $mM·L^{-1}$, RSA, and COD for both male and female players, while 4 $mM·L^{-1}$ was related to RSA for males only. The lack of a significant relationship between 4 $mM·L^{-1}$ and RSA ($p = 0.06$) in our female cohort may reflect the small sample size (n = 9). Interestingly, COD was correlated with SPPT final lap but not the 4 $mM·L^{-1}$ lap, despite the latter two variables being measured while players negotiated the same course. This likely reflects the maximal nature of the COD test and suggests that the neuromuscular requirements of the SPPT differ while running at maximal and submaximal intensities. Based on this data, we speculate that metabolic pathways, rather than neuromuscular properties, may be the dominant factor in determining 4 $mM·L^{-1}$ lap performance. However, further research is required to confirm this proposition.

We found RSA to be correlated with SPPT final lap and 4 $mM·L^{-1}$ lap for both males and females. This supports previous research that has advocated the importance of RSA qualities within elite squash (Wilkinson et al., 2012) and corroborates research from team sports, that have identified relationships between aerobic fitness and RSA (Aziz et al., 2000; Da Silva et al., 2010). This likely reflects a greater aerobic capacity enabling expedited recovery between sprints (Girard et al., 2011). We caution however, that despite the strong correlation observed between RSA and SPPT final lap, the RSA total time did not differentiate

HIGH and LOW performers. Whilst it may be a characteristic of this elite group (i.e. relative homogeneity) that resulted in no statistical difference overall, the weight of evidence still indicates RSA should be considered a '*gold'* training quality within squash (Table 2). Finally, we identified large and very large correlations between sum of 7 skinfolds and both SPPT 4 $mM \cdot L^{-1}$ lap and Final Lap, respectively. Whilst similarly strong relationships were not identified separately for males and females, this indicates body composition is an important measure when performance profiling across a large group of squash players, of varying abilities.

Physiological determinants

We also investigated the physiological determinants of the SPPT final lap, using a subset of players from the original cohort (n = 15). Correlations were made between SPPT performance and $\dot{V}O_{2max}$, movement economy, and 4 $mM \cdot L^{-1}$ lap, which provided a proxy for the lactate turnpoint. The very-large relationship identified between 4 $mM \cdot L^{-1}$ lap and SPPT final lap (r = 0.83) reinforces the conclusions from the first SPPT, regarding the role of cardiovascular fitness, when assessed in a sport-specific manner. The submaximal nature of monitoring the metabolic transition denoted by the 4 $mM \cdot L^{-1}$ lap, either alone or in conjunction with the 2 $mM \cdot L^{-1}$ lap (James et al., 2019), presents less interruption to ongoing training, compared with a maximal assessment. Therefore, blood lactate and/or HR monitoring during the SPPT, enables physiological monitoring to be implemented within squash, comparable to submaximal assessments conducted in other intermittent sports (Altmann et al., 2021).

$\dot{V}O_{2max}$ demonstrated a large positive correlation (r = 0.62) with SPPT final lap. Although the SPPT yields valid $\dot{V}O_{2max}$ values when conducting the test with a metabolic cart (James et al., 2019), it has been suggested that $\dot{V}O_{2max}$ alone may not discriminate within an elite group of squash players, as there is already a requisite threshold value (Wilkinson et al., 2012). The subset of players that were used to record cardiorespiratory measures may be considered a heterogenous group, as this group contained both males and females, with a spread of finishing scores from 58 to 88 laps. As a result, the measurement of $\dot{V}O_{2max}$ may not add additional value when compared to the measurement of finishing lap in an elite population, but remains relevant for monitoring physiological development of individual players.

We observed a non-significant relationship between SPPT and movement economy (r = 0.019), measured as the average submaximal oxygen consumption across the first four stages of the test. Whilst customary for assessing movement economy (Jones, 2006), expressing oxygen consumption relative to average velocity during the SPPT does not facilitate comparisons with traditional treadmill protocols, as the SPPT encompasses repeated changes of direction. Nevertheless, movement economy theoretically discriminates between players who perform squash-specific movements with a lower oxygen cost and/or expedited oxygen kinetics (Burnley and Jones, 2007). However, the non-significant relationship between movement economy and SPPT final lap indicates economy to be of little use as a standalone assessment within the SPPT, or when seeking to discriminate between players and/or predict performance. This is similar to endurance running, whereby, running economy distinguishes between athletes of similar $\dot{V}O_{2max}$ (Morgan et al., 1989), but alone does not predict performance as strongly as $\dot{V}O_{2max}$ or the lactate turn-point (McLaughlin et al., 2010; James et al., 2017b). The absence of a stronger relationship between movement economy and SPPT may reflect the interrelation of aerobic adaptations (James et al., 2017a; Jones et al., 2020) whereby increases in $\dot{V}O_{2max}$ or lactate thresholds result in a greater absolute oxygen consumption at submaximal intensities. As such, those with a high $\dot{V}O_{2max}$ may not routinely reveal a lower movement economy, compared with another player of lower $\dot{V}O_{2max}$. Notwithstanding that movement economy was not strongly correlated to the SPPT final lap, the assessment of submaximal oxygen consumption remains reliable during the SPPT (James et al., 2019) and therefore longitudinal tracking of this variable may still provide pertinent information to track individual physiological development.

Limitations

The practical challenges associated with recruiting elite, international standard squash players limited the sample size of this study, especially within our female cohort. Whilst a sample size calculation indicates suitable power to detect an effect within changes in SPPT final lap at the whole group level, some caution should be taken when interpreting the findings pertaining to female players. Future research should investigate how aerobic fitness parameters differ between elite male and female players. Our testing battery included assessments with standardized footwork patterns. Thus, we have not examined 'agility' as players require during matches. However, integrating lights or reactive cues within a fitness assessment may influence the outcome of the SPPT, RSA or COD, challenging the accurate interpretation of each physical quality. Moreover, during matches, players use a variety of situational cues to inform movement choice, which may be unrelated to generic visual or audible cues during a fitness assessment (Micklewright and Papapdopoulou, 2008). We did not include assessments of absolute or reactive strength. Leg strength appears important for delaying fatigue associated with repeated lunges and changes of direction within squash (Bennie and Hrysomallis, 2005) and associated joint stiffness has been shown to result in improved movement economy in other sports (Barnes et al., 2013). As such, future research should investigate these factors for strength and conditioning training prescription (Figure 2).

Practical Applications

The SPPT provides amateur and elite squash players a single assessment of squash-specific physical performance that differentiates between performance levels. Individual performance profiling should prioritise assessments of cardiovascular fitness (i.e. 4 $mM \cdot L^{-1}$), RSA, COD and body composition (Figure 2). Identifying a player's strengths and weaknesses across these key attributes allows training to be targeted to areas demonstrating the strongest associations with squash physical performance. Such training may include off-court 'interval' training, which provides a large cardiovascular stimulus, without high intensity accelerations, decelerations or changes of direction (James et al., 2021a). On-court training, such as ghosting using the layout of the SPPT and accompanying audio, can be used to provide a range of physiological stimuli, by manipulating running speeds, the number of sets and repetitions and rest intervals, as desired. We have previously shown such ghosting sessions to provide comparable internal and external training intensities to matchplay (James et al., 2021a).

Tracking the 4 mM·L^{-1} lap through regular, submaximal assessments, may offer a convenient athlete monitoring approach, negating a larger testing battery. A monthly assessment, at the start of a training week, minimizes training interruption (i.e. assessment represents a prolonged warm-up) and reduces the risk of injury and/or muscle soreness interruptions to training that may arise from maximal exercise testing (Horsley et al., 2020).

We observed stronger correlations between SPPT and RSA (r = -0.79), than for RSA Fatigue Index (r = -0.39), alluding to the importance of prioritizing absolute RSA performance time, rather than the decrement (Girard et al., 2011). Similarly, our data support the use of non-linear, squash-specific high-speed movement assessments such as COD (Wilkinson et al., 2009b), rather than straight-line assessments, such as the 5m sprint.

Conclusion

The SPPT offers a standalone assessment of squash physical performance, which can be enhanced with the collection of physiological data for individualized training prescription. Combining the SPPT with squash-specific assessments of RSA and COD enables physical performance profiles to be developed and by identifying individual strengths and weaknesses against normative data for these key assessments, training can be targeted to the most relevant training adaptations.

Acknowledgements
The authors would like to thanks the coaches and players at the Squash Racquets Association of Malaysia (SRAM) for enabling this research to be conducted. The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author who was an organizer of the study.

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Key points

- A squash-specific aerobic fitness test (SPPT) discriminated between higher and lower ranked squash players across final lap score and the lap corresponding to a blood lactate concentration of 4 mM·L^{-1}.
- Assessments of cardiovascular fitness (i.e. 4 mM·L^{-1} lap), repeated-sprint ability, change of direction speed and body composition appear highly pertinent for performance profiling of squash players.
- Sub-maximal blood lactate assessments may offer a convenient athlete monitoring approach within squash, negating the need for a larger testing battery.
- The SPPT offers a standalone assessment of squash physical performance, which can be enhanced with the collection of physiological data for individualized training prescription.

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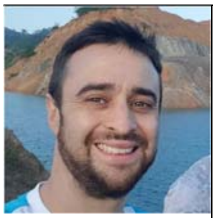

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