A review of sport-specific performance testing in squash

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OVERVIEW

The sport of squash has substantially developed since its founding in England in the early 1800s. Over 185 countries currently participate in the sport under a number of National Associations, all governed by the World Squash Federation (WSF) and the sport is currently bidding to become a sport in the 2020 Olympic Games.[25] Squash is a racket sport played on an indoor court measuring 9750mm by 6400mm.[29] A match is comprised of three or five games and can approach three hours in match duration.[17,20] There are three main disciplines of play: 'singles', 'doubles' and 'hardball squash doubles'. Athletes are categorised by gender, age, masters (men 35-70+ years and women 35-55 years), senior (over-19), junior (under 11/13/15/17/19 years), and level of play: recreational, regional, national and international.[25, 28, 29]

Squash is comprised of high intensity, short, intermittent repeated bouts. A rally is generally played within the range of 1.5-30s, with most rallies lasting 16-20s, and with about 7-8s of recovery periods in-between.[10,11,13,17,20] Rally durations and rest period depend upon performance level of the athlete.[17] The demands of squash suggest performance is determined by a combination of anaerobic and aerobic fitness; power, strength, speed, agility, balance and mobility combine along with tactical and technical skill, as well as awareness and control.[12, 20, 24] Heart rate (HR) generally exceeds 75% of predicted maximums, reaching a plateau at 80-90% of predicted maximum within the first few minutes.[1,2,4,7,19] In addition to this, relatively low mean blood lactate concentrations ([La–]b) range from 2-4 $mmol.l^{-1}$ but have been observed to rise to 10 $mmol.l^{-1}$;[17, 20] VO_{2max} means between 40 - 60 $ml.kg^{-1}.min^{-1}$ (>70% VO_{2max}) during competition have been reported.[6, 15, 19, 22, 23]

Physiological testing as a means to assess and improve performance is common practice in squash, as in the majority of sports. Testing in squash has taken place in both laboratory and field settings. However, laboratory-based testing of competition-level physiological demands is questionable, as laboratory testing (LT) and sport-specific testing (SST) depict different values of physiological parameters.[21,26] Müller et al[16] suggested an improvement in quality of training to be a prerequisite for improving performance. To establish an improvement, tests that assess sport-specific parameters to their entirety should be conducted.[16] The development of SST presenting methodologies that reflect game-play, simulating competition-level physiological demands, are therefore deemed of great benefit.

The aim of this review is to use evidence-based reasoning to appraise and critically evaluate available research conducted within and relating to squash, with a focus on sport-specific testing. The objectives of this review are to (a) observe the differences in methodology of LT and SST, (b) to observe the developments and modifications of SST within squash and (c) to observe the validity of these developments and modifications.

Methods

A literature search was conducted through the following online databases: Google Books, Google Scholar, PubMed, SportDiscus®, and Science Direct, using the following key words: 'squash', 'squash AND performance', 'squash AND physiology', 'squash AND aerobic fitness', 'squash AND anaerobic fitness', 'squash AND testing', 'squash AND sport-specific testing', 'squash singles'.

Once online articles had been gathered they were categorised as follows:

- **method:** SST/LT/both SST and LT;
- **performance level:** recreational/elite;
- **gender:** male/female/both male and female.

A manual examination of relevant references was conducted once online articles had been gathered. These articles were then obtained and placed in the appropriate category. The literature search and manual examination resulted in[2,291] citations; however, only 23 of these met the inclusion/exclusion criteria below and were thus included in this review.

INCLUSION CRITERIA:

(a) Participants were tested individually or with one opponent; reflective of 'singles' game play

(b) Physiological responses were assessed

(c) LT: Valid and reliable method used for testing

(d) SST: A definitive outcome of the validity of the testing method was observed and stated

(e) SST: methodology and results presented determinants of Moore and Wilkinson's[18] validity criteria as shown in Table 1.

EXCLUSION CRITERIA:

(a) No peer-reviewed publication reference was obtainable

(b) No direct presentation of contribution to aim or objectives

(c) Athletes participating in 'doubles' or 'hardball squash doubles' disciplines.

Results

LABORATORY TESTING VS SPORT-SPECIFIC TESTING

Throughout the literature focused on squash, observations and assessments of an athlete's physiological profiles has been founded upon resultant values derived from LT, SST and observations during play. The data available includes a variety of testing protocols within LT and SST. A diversity of populations has been used in the literature varying in age, gender and performance level.

Testing protocols within LT, SST and observations during play differ from study to study, although observations of common physiological parameters (eg, HR (beat/min), HE ($\%_{max}$), VO_{2max} (ml/kg/min) and [La-]b ($mmol.l^{-1}$) seem to be relatively similar. Methods used during LT of squash players vary from incremental treadmill tests to sprint tests and Wingate tests, all of which require different physiological and biomechanical demands for maximal effort.[15,22,26] In addition to this, studies that have used the same or similar titles for the LT protocol also have slight variations. Todd and Mahoney,[22] Wilkinson et al[26]

Table 1: Validity criteria table (based on Moore and Wilkinson[18])

VALIDITY DETERMINANT	CRITERIA
Criterion validity	Comparison of procedures between the newly developed test and those already deemed valid and of a good standard
Logical validity	The ability of the test to assess relevant and vital parameters of performance
Construct validity	The ability of the test to distinguish between participants from: (i) Sports with different characteristics and/or (ii) Different performance levels with a sport

Table 2: Incremental treadmill test methodology comparison table

LT METHOD: INCREMENTAL TREADMILL TEST					REFERENCES
Start speed (km/h)	Speed increase rate	Start gradient (%)	Gradient increment (%)	Gradient increment rate (mins)	
12.9	None	Not reported	2.5	3	22
13	1 $km.h^{-1}$ per minute	0	1 (after a speed of 16 $km.h^{-1}$ was reached)	1	26
10	2 km/h per 3 minutes	Not reported	0	Not reported	14

Table 3: Testing protocols used in sport specific tests of squash performance

SST METHOD: TESTING PROTOCOL	REFERENCES
'Incremental squash test' Participants completed stages of two bouts consisting of 9 sequences (2 forward, 3 lateral and 4 backwards) with 10s or active recovery. The test was performed until volitional exhaustion.	7
'Squash stimulation protocol' Participants completed four rallies of different lengths (6-11 stimulated shots) with 7s recovery periods between each. Each rally provoked a different movement patterns determined by pre-recorded audio signals; running to court positions indicated and returning back to the 'T' (see appendix 1).	11
'Squash specific multiple-sprint test' Participants completed a course (see appendix 2). One completion of the course equated to 2 laps. Participants simply had to complete the course in the quickest time possible in 10 attempts with 20 s recovery periods in-between.	26

and Mahoney and Sharp[14] all referred to the test conducted as an 'Incremental treadmill test' (Table 2).

However, as can be seen in Table 3, all three studies conducted different protocols. These variations have the potential to influence results of the studies due to the difference in demands on physiological processes. For example, Hermansen and Saltin[9] observed higher oxygen uptake in participants when running maximally uphill[30] than when running maximally with no incline. A further reduction in validity for LT occurs in the increasing of gradient as in Todd and Mahoney[22] and Wilkinson et al[26] due to Hermansen and Saltin's[9] findings, but as the squash court is a level surface with no inclines this does not apply.

Protocols within SST also exhibit variations (Table 4) due to more recent development to increase validity and reliability. Due to the multiplicity of methods used within LT and SST, results produced cannot be conclusively compared.

Although it is difficult to compare results across tests conclusively, values elicited from SST hold greater relevance for squash performance. Laboratory testing does not account for all aspects of squash performance. For example, treadmill-based tests, such as those used by Todd and Mahoney,[22] Wilkinson et al[26] and Mahoney and Sharp,[14] do not enable researchers to observe movement patterns associated with performance during play (eg, jumping and change of direction). SST protocols have been developed through observations during competition and adaptations of previous studies where limitations were addressed.[26] The development of SST has aimed to observe and assess squash players under conditions as similar to competition as possible. It can therefore be expected that SST protocols will place the body under similar demands to that of competition, taking into account all performance components that contribute to physiological responses. In addition to this, the testing environment is more familiar and natural to the athletes (floor surface, footwear, court layout) and potentially in some testing, athletes will also be able to use their own rackets as in competition. Aspects of SST such as these cause results to be more relevant to performance, presenting valid indications of necessary adaptations to training programs. Although LT allows for precise control of the testing environment, in order to achieve more ecologically valid test data, practitioners need to control environmental conditions while also ensuring any tests reflect the physiological demands of squash and also achieve the validity criteria of SST (Table 1).

Sport-specific testing development

As previously mentioned, SST in squash is constantly developing. Based on the aforementioned search strategy, there are currently only three studies – Steininger and Wodick,[21] Girard et al[7] and Wilkinson et al[26] – which have developed SST protocols for assessment and were designed to evaluate the validity of these protocols. In all cases, these tests are performed on a squash court. Methodologies and results are summarised in Table 4.

TESTING PROTOCOL DEVELOPMENT: VALIDITY AND RELIABILITY

Steininger and Wodick[21] was the first of the three studies to develop an SST protocol that was conducted in a familiar environment (squash court), simulating physiological demands of competition (Table 4). Due to the novelty of their study, it cannot fully satisfy the 'criterion validity' factor of Moore and Wilkinson's[18] validation criteria, but the methodology and results indicate an achievement of both the 'logical validity' and 'construct validity' (Table 1).[21] During competition, squash players undergo several randomised movement patterns on the court during each rally.[24] However, Steininger and Wodick did not incorporate this aspect of the nature of squash play.[21] Steininger and Wodick's[21] observations of the increased validity of results produced from ST were further developed by Girard et al[7] (Table 4).

Girard et al[7] replicated a similar SST court set-up with the adaptation of a PC used to control movement directions and velocities. The use of the PC enabled this study to overcome the limitation of randomised movement in Steininger and Wodick's study with the integration of randomised movement patterns.[21] Participants underwent 36 'dashes' over 3 minutes during intensity level 1 in Steininger and Wodick's study,[21] equivalent to 1 dash/5s with no indication of a warm-up period. However, the first intensity level of the Girard study followed a warm-up period (3 stages), consisting of 2 bouts of 9 shuttle runs in 38s. This indicates

Table 4: Studies comparing squash athletes and non-squash athletes' performance in LT and SST testing

METHOD [(1): LT/ (2): SST]	RESULTS	REFS
(1) Treadmill ergometry: Beginning speed of 1.67 m/s (6km/h) with 5% gradient. Speed increase of 0.55 m/s (2km/h) every three minutes until exhaustion (2) Field test: Players ran from a central point 'T' to balloons when their corresponding bulb lit up, striking the balloon with technical correctness. Each level being 3mins, the bulb lit initially at a rate of 12 pulses/min during the first level. Each level progressed with the addition of 6 pulses/min until exhaustion. 45s rest period took place after each level.	A significant correlation was identified between participants' squash rank-order in junior squash players and field test results (r - 0.09; p<0.01). However the LT presented a lower correlation with rank order (r - 0.52; P>0.05). The field test elicited significantly higher values in [La–]b (8.0±1.8 vs. 6.1±0.6) and faster recovery rates than that of the LB in junior squash players.	21
(1) Treadmill incremental test: Starting workload of 10 km/h with an increase of 1km/h every 2 minutes until volitional exhaustion. Incline is constant at 0%. (2) Squash-specific graded test: Each stage consisted of 2 bouts of 9 random displacement shuttle runs (2 forward, 3 lateral and 4 backwards) from the central point to a target and returning back to the central point. A powerful shot was performed under 40cm towards the front wall. Each displacement and stage was followed by 10s active recovery. Participants had a 30s rest after stage 3 (end of warmup) and beginning of stage 4. Sequence 1 had a duration of 38s, decreasing by 1.8s for stages 1-3 and 0.9s for stages 4-17. Computer software calculated velocities and directions to ensure randomisation reflective of game play.	Maximum loads exhibited significantly higher VO_2 (63.6±3.0 vs. 54.9±2.5 ml/min/kg; P=0.001, VCO_2 (68.5±3.5 vs. 51.4±15.2 ml/min/kg) and breathing frequency (59.1±6.6 vs. 50.2±8.7 breaths/min) in the ST than the LT. No significant difference was observed from SST and LT in time to exhaustion (1056±180s vs. 962±71s) although a strong correlation was observed between time to exhaustion and player ranking in the SST but was not reflective of the LT.	7
(1) Incremental treadmill test: 5 min warmup at 10 km.h^{-1} (0% gradient) was undertaken prior to testing. Speed began at 13 km.h^{-1} (0% gradient). A gradient of 0% was maintained while speed was increased by 1 km.h^{-1} every min up to 16 km.h.$^{-1}$ After which a speed of 16 km.h^{-1} was maintained while the gradient increased by 1% per minute until volitional exhaustion. (2) Incremental SST: Participants began on a central point 'T'. When a signal was heard, participants had one minute to reach the indicated target (2 front corners and two back corners). Upon reaching the target, one foot had to be placed on the target and a forceful shot of choice mimicked down the nearest court sidewall. Stage 1 consisted of 14 movements within the stage of 1 minute. The number of movements within each stage increased continuously at a rate of 1 move per minutes until volitional exhaustion.	Squash players exhibited significantly greater time to exhaustion on the SST than runners (775±103 vs. 607 ± 81s; P=0.003). Whereas runner presented significantly greater time to exhaustion in the LT than squash players (521 ± 135 versus 343 ± 115 s; p= 0.013). There was no significant difference between squash players and runners VO_{2max} (52.2±7.1 vs. 56.6±4.8 ml.kg^{-1}.min^{-1}; P=0.17) or HR_{max} (190±7 vs. 182±11 beats.min^{-1};p=0.12) in the ST or LT. LT performance promoted significantly higher VO_{2max} in runners (58.6± 7.5 ml.kg^{-1}.min^{-1}) than squash players 49.6±7.3 ml.kg^{-1}.min^{-1}; p=0.29). No significant difference was found between squash players and runners in HR_{max} 183 ± 10 vs. 191 ± 13 beats·min^{-1}, P = 0.17). Squash players achieved significantly higher VO_{2max} values in the SST than the LT (52.2 ± 7.1 vs. 49.6 ± 7.3 mL·kg^{-1}·min^{-1};P= 0.017) although there was no significance between HR_{max} in either test (190 ± 7 vs. 191± 13 beats·min^{-1}; P = 0.711). Runners did not present significant HR_{max} or VO_{2max} values in either ST or LT (182 ± 11 vs. 183 ± 10 beats·min^{-1}; P = 0.90 and 56.6 ± 4.8 vs. 58.6 ± 7.5 mL·kg^{-1}·min^{-1}; P = 0.45).	26

1 run/4.2s. Both studies initially simulated durations of rally bouts, thus increasing the specificity and likeness to competition.[20] However, it can be suggested that Girard et al maintained a greater similarity to competition as 38s per sequence decreased by 1.8s (1 run/2s) and then 0.9 (1 run/ 2.1s) in the latter stages.[7] By contrast, Steininger and Wodick increased by 6 dashes per level until exhaustion.[21] This increase would cause participants to be completing 1 run/1.3s by level 11, which is 6 stages short of Girard's final stage. Thus this is not reflective of competitive rally duration, although the significance of this time difference and effect size will need to be established to identify the importance to performance in squash competition.

More recently, Wilkinson et al[26] further modified the SST protocols of Steininger and Wodick[21] and Girard et al.[7] Wilkinson et al adapted the dimensions of the court setup in response to match analysis undertaken by Vućković et al[24] and Hughes and Roberts.[10] This research was also influential in the creation of movement patterns potentially creating a greater likeness to competition, increasing validation of the SST to simulate demands. Wilkinson et al[26] were able to overcome the limitations of Steininger and Wodick[21] and Girard et al in audio feedback responses by instigating movement patterns with audio signals. Although this did not directly replicate the audio response of the ball hitting and rebounding off the wall during play, it did allow participants to utilise sound during the study in the same way as during competition. Once again, the likeness to competition is developed further. In addition, Wilkinson et al[26] satisfied all three of Moore and Wilkinson's validation criteria.[18]

PHYSIOLOGICAL MEASUREMENTS

Modifications were also seen in physiological measurements reported by authors validating squash-specific tests. Steininger and Wodick utilised the 45s rest periods between each intensity level to obtain blood and ECG data for analysis;[21] Girard et al and Wilkinson et al, however, used valid technology (K4b; Cosmed, Rome, Italy and Metamax 3B, Cortex Biophysik, Leipzig, Germany) to enable the data collection of physiological responses throughout the test.[7,26] Averages were calculated every 30s in both studies. This modification enabled greater validity regarding collection of physiological measurements due to the equipment used. It also allowed for physiological response data to be obtained continuously during testing that would have previously only been possible to achieve during LT (Table 4 and 6).

PARTICIPANTS

It is also important to note that, in studies examining sport-specific testing for squash, participant characteristics vary considerably. To further increase the validity and reliability of SST, particular attributes of participants should be identified in future research on this topic. Literature indicates the impacts of age, performance level and sporting background on physiological responses such as HR and VO_{2max}.

AGE AND GENDER

The effect of age on physiological responses is evident in a number of sports including squash. Brown et al observed elite male and female junior (17.7 ± 0.2 years and 16.7 ± 0.3 years) and senior (24.9 ± 0.6 years and 25.6 ± 1.7 years) squash players during incremental treadmill test to volitional exhaustion.[3] Males presented greater VO_{2max} values than females in both elite junior and senior players.

Table 5: Anthropometric data of SST studies

PARTICIPANTS' SPORT	LEVEL OF PERFORMANCE	GENDER	AGE (YRS)	BODY MASS (KG)	HEIGHT (CM)	REFERENCE
Squash	-	Male (7) Female (6) (Males and females were not distinguished between in results)	-	-	-	21
Squash	Well-Trained	Male	24.9±4.1	72.1±6.1	177.0±5.9	7
Squash Distance Running	Trained	-	30±11.2 29.6±9.4	81.3±10.2 69.4±6.7	180±4 177±5	26

Table 6: Physiological responses of squash players to SST

PARTICIPANTS'	RESULTS (MEAN ± SD)				
	HR (beats/min)	HR (% max)	$VO_{2\,max}$ (ml/kg/min)	BLA (mmol.l^{-1})	REFERENCE
Squash	185.3±6.5	-	-	8.0±1.8	21
Squash	170.5±13.8	87.8±4.8	53.6±2.5	-	7
Squash	190±7	-	52.2±7.1	9.0±1.3	26
Distance Running	182±11	-	56.6±4.8	9.3±1.2	

A significantly greater VO_{2max} was also found in junior compared to senior players of both genders. This suggests that results should distinguish between the age categories of competitors and – unlike Steininger and Wodick (Tables 5 and 6) – between male and female participants. However, Brown et al's observations were based on LT protocol.[3] To increase the relevancy and validity of these findings to squash competition, it would be favourable to conduct future research using SST protocols.

SPORTING BACKGROUND AND PERFORMANCE LEVEL

The physiological and biomechanical demands for each sport are different. Wilkinson et al present the impact of this through observations through squash LT and SST of the performances of both squash players and distance runners in an incremental treadmill test (Table 4).[26] It is evident that the body adapts to the nature of play and training undertaken as well as establishing physiological and biomechanical modifications that lead to success within the particular sport.

It has been found that physiological responses to physical activity differ with an athlete's performance level.[5] Reilly and Halsall observed match-play between aged-matched competitive and recreational squash players.[19] Older competitive players exhibited a significantly lower $\%HR_{max}$ response to match-play than their recreational equivalent. Similarity between $\%HR_{max}$ of younger and older competitive players and significantly higher VO_{2max} values of competitive players indicates the training effect of squash on physiological responses during play. In addition to this, subjective responses of whole body, breathing and muscles rate of perceived exertion to match-play are significantly higher in recreational athletes than competitive players.[19] To increase validity of SST and to satisfy Moore and Wilkinson's validity criteria,[18] participants' sporting background and performance levels should be clearly identified and defined, and results should distinguish between participants.

The importance of squash-specific, multiple sprint performance

SST for squash continues to evolve, with recent research by Wilkinson et al underlining the importance of lower body, multiple sprint, and change of direction performance as all being key to assessment of physiological capabilities and performance potential in squash.[27] In this study, Wilkinson et al examined 31 players within the England squash performance programme who were separated into 'senior', 'transition' and 'talented athletes scholarship scheme' (TASS) categories. Players were assessed for aerobic endurance, using the 20m shuttle run test, countermovement and reactive strength drop jumps, a change of direction speed test and a multiple sprint test. The change of direction speed test and the multiple sprint test both used the format of the Wilkinson et al SST.[26] In the case of the change of direction speed test, performers undertook three attempts separated by 2 min recovery between each attempt. The multiple sprint test comprised 10 attempts of the test with each attempt separated by 20s. The sum of all 10 attempts was used to reflect multiple sprint ability.

Irrespective of sex, senior players outperformed TASS players on all tests conducted except aerobic endurance performance. Players classed as seniors had significantly better multiple sprint ability than transition players, while transition players outperformed TASS players on the reactive strength test. Reactive Strength Index (RSI) therefore appears to be effective in discriminating between players of different standards.[27] This is potentially because the RSI reflects the ability to reverse an eccentric action into a concentric action, a key aspect of change of direction speed.

When world ranking was considered, multiple sprint ability, fastest multiple sprint repetition and change of direction speed was significantly related to rank in men, and fastest multiple sprint test repetition was significantly related to rank. These results confirm that high-intensity, variable direction exercise capabilities are important for success in elite squash. Thus, coaches may want to prioritise this within needs analysis and programme development for squash performers. Moreover, by virtue of the association between world rankings and multiple sprint test performance in this study, the SST originally developed by Wilkinson et al[26] shows good ecological validity and should be recommended

as a diagnostic tool for the assessment and monitoring of squash performers.

Conclusion: limitations and implications for strength and conditioning

This review presents the benefit and limitations of the transitional development from LT to SST and the modification of SST in squash. SST proposes a greater ability to produce data that is more reflective and specific to physiological responses to competition than LT. The development of Steininger and Wodick's[21] SST protocol, initially by Girard et al[7] and then further by Wilkinson et al,[26] is shown to be valid.[18] The developments progress in specificity of competitive simulation while maintaining validity through presentations of discrimination between participants and correlations between rank-order and SST performance.

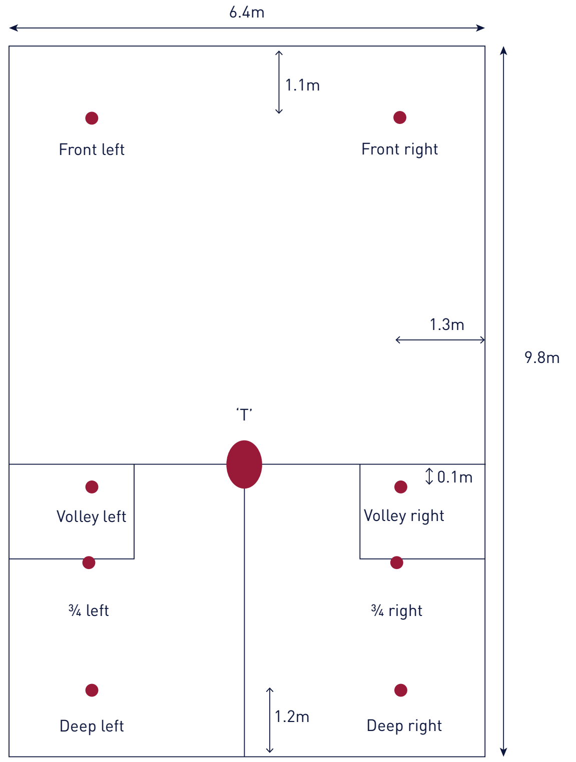
A main aspect of SST is the lack of standardisation of protocols. This is understandable due to the fairly recent development of SST protocols assessing their validity. Recent research from Wilkinson et al has however identified a protocol that is ecologically valid, related to the physiological demands of squash and one that can be used for athlete testing and potentially development of sport specific change of direction speed.[26, 27] Coaches and scientists working with squash athletes should therefore be encouraged to use this protocol for both the determination of change of direction speed and also squash specific multiple sprint ability.

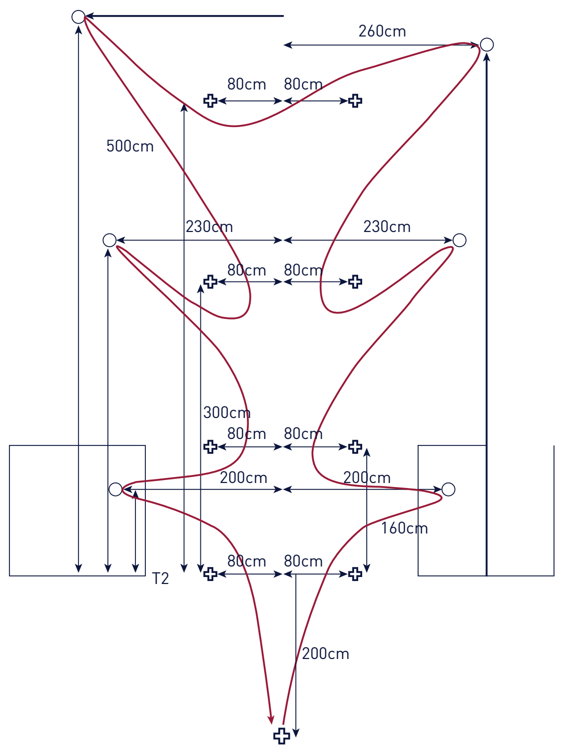
Collectively, the data presented in this systematic review suggest that coaches and athletes should focus on:

- Developing the ability to make multiple, frequent and rapid changes of direction using squash specific movement patterns

- Developing lower body explosiveness and multiple sprint capacity
- Placing less emphasis on development of aerobic endurance
- Considering reactive strength index as a diagnostic measure due to its association with other sport-specific measures of change of direction speed and multiple sprint ability reported in the literature
- Using the Wilkinson et al sport-specific squash test as a key protocol of athlete assessment and monitoring of change of direction speed and multiple sprint ability.

Appendix figures





ix. Appendix

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Appendix 1.
Court positioning of Squash Simulation Protocol (Kingsley et al 2006)

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Appendix 2.
Course dimensions of squash-specific multiple-sprint test (Wilkinson et al 2010)

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