Sports Med
DOI 10.1007/s40279-014-0287-2

REVIEW ARTICLE

The Science of Badminton: Game Characteristics, Anthropometry, Physiology, Visual Fitness and Biomechanics

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Abstract Badminton is a racket sport for two or four people, with a temporal structure characterized by actions of short duration and high intensity. This sport has five events: men's and women's singles, men's and women's doubles, and mixed doubles, each requiring specific preparation in terms of technique, control and physical fitness. Badminton is one of the most popular sports in the world, with 200 million adherents. The decision to include badminton in the 1992 Olympics Game increased participation in the game. This review focuses on the game characteristics, anthropometry, physiology, visual attributes and biomechanics of badminton. Players are generally tall and lean, with an ectomesomorphic body type suited to the high physiological demands of a match. Indeed, a typical match characteristic is a rally time of 7 s and a resting time of 15 s, with an effective playing time of 31 %. This sport is highly demanding, with an average heart rate (HR) of over 90 % of the player's maximal HR. The intermittent actions during a game are demanding on both the aerobic and anaerobic systems: 60–70 % on the aerobic system and approximately 30 % on the anaerobic system, with greater demand on the alactic metabolism with respect to the lactic anaerobic metabolism. The shuttlecock has an atypical trajectory, and the players perform specific movements such as lunging and jumping, and powerful strokes using a specific pattern of movement. Lastly, badminton players are visually fit, picking up accurate visual information in a short time. Knowledge of badminton can help to improve coaching and badminton skills.

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Key Points

Badminton is a highly demanding game characterized by intermittent actions, with energy being provided by both the aerobic (60–70 %) and anaerobic (30 %) systems.

Elite players are able to launch the shuttlecock at high velocity due to the efficiency of a sequential proximo-distal joint action chain combined with the use of racket deflection.

Badminton players are visually fit, picking up accurate visual information in a short period of time.

1 Introduction

Badminton is one of the most popular sports in the world, with 200 million adherents [1]. Originating in China and created in England [2], it is the national sport of various Asian countries. It can be practiced by anyone regardless of age or experience [3, 4], and is the fastest racket game [5–10].

Performance factors in badminton are many-fold, revealing the sport's complexity. Badminton is characterized by high-intensity, intermittent actions. This sport has five events: men's and women's singles, men's and women's doubles, and mixed doubles, each requiring specific preparation in terms of technique, control and physical fitness. The decision to include badminton in the 1992 Olympics Game increased participation in the game. Badminton games are generally played in a tournament with one to three matches over the course of 4 or 5 days.

Published online: 31 December 2014

The Badminton World Federation Super Series, consisting of 12 tournaments per season with 32–44 singles/doubles players competing at each tournament, was established in 2006 and is widely regarded as the highest standard of badminton competition in the world.

Investigations specific to badminton performance include studies on match analysis (timing and notational) and physical profiling. Additional studies provide information on the anthropometry of players and the biomechanics of specific movements and strokes.

During a match, players are required to maintain a high level of intensity for as long as possible. Energy expenditure depends on players' morphological factors and displacement efficiency. The players focus their attention on the shuttlecock and their opponents in order to anticipate their displacement. Stroke preparation and the shuttlecock's atypical and surprising flight trajectory [11, 12] require considerable skill in order to hit it the full length of the court [12]. Players adapt their movements using biomechanical factors of efficiency to respond to the full set of visual information. This requires quick changes of direction, jumps, lunges at the net and rapid arm movements from a variety of postural positions [13, 14]. These factors have also influenced physiological demands. The objective of this review was to summarize current literature on match demands and the physical and physiological characteristics of badminton players, and to identify directions for future research and for better training designs.

We conducted a literature search for English and non-English articles in the following databases: PubMed, EBSCOhost, PsycINFO, ScienceDirect, Cairn, and Web of Science. An additional search was performed on the Internet using Google Scholar and ResearchGate. Keywords, and combinations of these words, used to search the databases comprehensively were 'badminton', 'biomechanics badminton', 'physiology badminton', 'notational badminton', 'temporal badminton', 'shuttlecock', 'aerodynamic shuttlecock', 'racket deflection', 'visual badminton', 'anthropometry badminton player', 'kinematic stroke badminton', 'racket sports', 'biomechanics racket sports', 'brain badminton', 'injury badminton' and 'performance badminton'. Database searches covered a period from 1968 to August 2014. Research articles were included if they reported experimental studies using badminton to determine performance in sport.

2 Badminton Match Demands

Badminton is a racket sport in which the temporal structure of an individual game or match is characterized by actions of short duration and high intensity [15] coupled with short rest periods. Several studies have sought to characterize this structure and the different scoring systems, as new scoring was adopted in August 2006 [16]. The overall winner is the winner of two out of three sets played to 21 points. Under the old scoring system, sets were played to 15 points (11 for women).

2.1 Temporal Structure of a Badminton Match

Competitive matches last 40 min [15, 17–20] to 1 h [21]. Studies report on the temporal characteristics of the game by measuring several variables, such as the match duration (time that elapsed from the first serve until the shuttle hit the ground for the last time), rally time (time elapsed from the serve until the shuttle hit the ground), rest time (in each innings, the time elapsed from the time the shuttle hit the ground until the racket hit the shuttle for the following serve), effective playing time (sum of the rally times divided by the match duration multiplied by 100), shots per rally (the total number of times the shuttle was hit by both players from the serve until it hit the ground), work density (rally time divided by rest time multiplied by 100) and shot frequency (number of shots divided by effective playing time) [15, 18, 20, 22–26] (see Table 1).

Match duration, work density and rest time are greater ($p < 0.05$) in men's singles (MS) than in women's singles (WS) [20, 22]. Mean badminton game characteristics [15, 18, 20, 22–26] are match duration (MS = 1,885.08 s; WS = 1,365.03 s), rally time (MS = 7.66 s; WS = 6.1 s), rest time (MS = 15.4 s; WS = 14.0 s), effective playing time (MS = 32.1 %; WS = 29.8 %), shots per rally (MS = 6.8; WS = 5.4), work density (MS = 0.49; WS = 0.43) and shot frequency (MS = 1.021 s^{-1}; WS = 0.89 s^{-1}).

2.2 Notational Analysis of Badminton Matches

Notational analysis provides an objective examination of individual performance through the analysis of chosen variables and is useful for coaches and players for improving performance [15, 18, 20, 22, 24, 26–28] since time spent in various aspects of a match, shot selection, and positions or shot methods of the last shot have often been used as indicators of notational analysis for evaluating badminton [15, 18, 20, 22, 24, 27, 28]. The different shots are defined in the following manner: the smash is an aggressive overhead shot with a downward trajectory, the clear is an overhead shot with a flat (offensive clear) or rising trajectory (defensive clear) towards the back of the opponent's court, the drop is a smooth shot from above the head with a downward trajectory towards the front of the court, the net shot is a precise shot from near the net, which includes the net drop, the lob (offensive shot with a flat trajectory towards the back of the opponent's court and

Table 1 Comparative results of the timing structure of a badminton game

Study	Variables	Subject (*n*)/condition	Male results	Female results
Old scoring[a]				
Chen et al. [18]	Match duration	International (16)/S	2,754.6 ± 178.9 s	NS
Ming et al. [24]		Young national (16)/R	24.06 ± 2.38 min	18.30 ± 6.09 min
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	2,378.0 ± 387.9 s	1,696.1 ± 170.4 s
Abián et al. [26]		Olympic Games (40)/R	1,124.6 ± 229.9 s	NS
			1,260.3 ± 267.1 s	NS
Cabello Manrique et al. [15]		International (11)/R	1,689.33 ± 312.89 s	NS
Chen et al. [18]		International (16)/S	1,949.7 ± 147.6 s	NS
Chen et al. [23]		International (10)/S	29 ± 3 min	NS
Cabello et al. [20]		Top national (79)/R	2,090 ± 921 s	1,638 ± 930 s
Ming et al. [24]		Young national (16)/R	17.27 ± 2.67 min	17.14 ± 0.97 min
Old scoring[a]				
Chen et al. [18]	Rally time	International (16)/S	7.9 ± 0.2 s	NS
Chen et al. [23]		International (10)/S	6.2 ± 1.0 s	NS
Ming et al. [24]		Young national (16)/R	4.63 ± 0.49 s	4.03 ± 0.59 s
Docherty [108]		Highly skilled (42)/S	10.0 ± 1.4 s	NS
		Medium skilled/S	9.7 ± 1.8 s	NS
		Lowly skilled/S	10.4 ± 1.3 s	NS
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 9.0 ± 0.9 s	Set 1: 7.8 ± 1.5 s
			Set 2: 9.1 ± 1.4 s	Set 2: 8.1 ± 1.7 s
Abián et al. [26]		Olympic Games (40)/R	9.0 ± 1.1 s	NS
			10.4 ± 2.1 s	NS
Cabello Manrique et al. [15]		International (11)/R	6.4 ± 1.25 s	NS
Chen et al. [18]		International (16)/S	8.2 ± 0.2 s	NS
Chen et al. [23]		International (10)/S	6.0 ± 0.6 s	NS
Faude et al. [25]		International (12)/S	5.5 ± 4.0 s	NS
Cabello et al. [20]		Top national (79)/R	7.3 ± 1.3 s	6.3 ± 1.4 s
Ming et al. [24]		Young national (16)/R	4.62 ± 0.86 s	4.16 ± 0.24 s
Old scoring[a]				
Ming et al. [24]	Rest time	Young national (16)/R	10.29 ± 1.42 s	10.18 ± 1.51 s
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 24.1 ± 3.8 s	Set 1: 17.6 ± 2.4 s
			Set 2: 25.2 ± 4.6 s	Set 2: 18.2 ± 3.5 s
Abián et al. [26]		Olympic Games (40)/R	24.7 ± 4.3 s	NS
			26.7 ± 4.6 s	NS
Cabello Manrique et al. [15]		International (11)/R	12.93 ± 2.68 s	NS
Faude et al. [25]		International (12)/S	11.4 ± 6.0 s	NS
Cabello et al. [20]		Top national (79)/R	14.2 ± 3.4 s	13.7 ± 4.2 s
Ming et al. [24]		Young national (16)/R	9.71 ± 1.32 s	10.53 ± 0.35 s
Old scoring[a]				
Chen et al. [23]	Effective playing time	International (10)/S	38.5 ± 3.5 %	NS
Ming et al. [24]		Young national (16)/R	31.19 ± 3.32 %	28.37 ± 0.31 %
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 28.1 ± 3.4 %	Set 1: 31.4 ± 2.6 %
			Set 2: 27.3 ± 2.4 %	Set 2: 31.3 ± 2.1 %
Abián et al. [26]		Olympic Games (40)/R	27.7 ± 2.9 %	NS
			28.0 ± 2.7 %	NS

Table 1 continued

Study	Variables	Subject (*n*)/condition	Male results	Female results
Chen et al. [23]		International (10)/S	36.4 ± 2.4 %	NS
Faude et al. [25]		International (12)/S	31.2 ± 2.8 %	NS
Ming et al. [24]		Young national (16)/R	32.22 ± 3.34 %	28.30 ± 0.77 %
Old scoring[a]				
Chen et al. [18]	Shot per rally	International (16)/S	7.5 ± 0.1	NS
Chen et al. [23]		International (10)/S	6.0 ± 1.2	NS
Ming et al. [24]		Young national (16)/R	4.77 ± 0.47	3.58 ± 0.42
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 9.7 ± 0.8	Set 1: 7.1 ± 1.6
			Set 2: 9.9 ± 1.4	Set 2: 7.4 ± 1.7
Abián et al. [26]		Olympic Games (40)/R	9.8 ± 1.1	NS
			11.1 ± 2.2	NS
Cabello Manrique et al. [15]		International (11)/R	6.0 ± 1.2	NS
Chen et al. [18]		International (16)/S	8.4 ± 0.2	NS
Chen et al. [23]		International (10)/S	5.9 ± 0.8	NS
Ming et al. [24]		Young national (16)/R	4.74 ± 0.78	3.48 ± 0.10
Old scoring[a]				
Chen et al. [23]	Work density	International (10)/S	0.63 ± 0.11	NS
Ming et al. [24]		Young national (16)/R	0.48 ± 0.07	0.40 ± 0.01
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 0.38 ± 0.06	Set 1: 0.45 ± 0.05
			Set 2: 0.36 ± 0.04	Set 2: 0.44 ± 0.04
Abián et al. [26]		Olympic Games (40)/R	0.37 ± 0.05	NS
			0.39 ± 0.05	NS
Cabello Manrique et al. [15]		International (11)/R	0.49 ± 0.06	NS
Chen et al. [23]		International (10)/S	0.57 ± 0.06	NS
Faude et al. [25]		International (12)/S	0.51 ± 0.34	NS
Cabello et al. [20]		Top national (79)/R	0.53 ± 0.12	0.47 ± 0.08
Ming et al. [24]		Young national (16)/R	0.46 ± 0.07	0.40 ± 0.02
Old scoring [a]				
Chen et al. [18]	Shot frequency	International (16)/S	0.98 ± 0.01 s^{-1}	NS
Chen et al. [23]		International (10)/S	1.05 ± 0.08 s^{-1}	NS
Ming et al. [24]		Young national (16)/R	1.03 ± 0.47 s^{-1}	0.89 ± 0.60 s^{-1}
New scoring[b]				
Abian-Vincen et al. [22]		Olympic Games (20)/R	Set 1: 1.08 ± 0.04 s^{-1}	Set 1: 0.91 ± 0.04 s^{-1}
			Set 2: 1.09 ± 0.03 s^{-1}	Set 2: 0.92 ± 0.06 s^{-1}
Abián et al. [26]		Olympic Games (40)/R	1.09 ± 0.03 s^{-1}	NS
			1.07 ± 0.04 s^{-1}	NS
Cabello Manrique et al. [15]		International (11)/R	0.93 ± 0.11 s^{-1}	NS
Chen et al. [18]		International (16)/S	1.05 ± 0.02 s^{-1}	NS
Chen et al. [23]		International (10)/S	1.03 ± 0.07 s^{-1}	NS
Faude et al. [25]		International (12)/S	0.92 ± 0.31 s^{-1}	NS
Ming et al. [24]		Young national (16)/R	1.03 ± 0.22 s^{-1}	0.84 ± 0.31 s^{-1}

Data are expressed as mean ± SD

R real match, *S* simulated match, *NS* not specified, *SD* standard deviation

[a] Old scoring (match-game 15 points for males and 11 points for females)

[b] New scoring (match-game 21 points for both)

defensive shot with a rising trajectory) and the kill (aggressive shot with downward trajectory), while the drive is a powerful shot made at middle body height and in the middle of the court with a flat trajectory.

For each player, each shot is identified and categorized in terms of when it is played, the type of shot selected [22, 24, 27, 29] (see Table 2) and the player's position when the shot is played [22, 24, 30] (see Table 3). The smash [22, 26, 31] (29.1 ± 8.4 %) and the drive [22] (6.3 ± 3.9 %) were used more frequently in MS in the last shot of the rallies, and the drop (9.0 ± 6.0 %) in WS [22, 29]. There were no significant differences in the frequency distribution of the other strokes [22]. During the match, male players hit the shuttlecock more often from near the net [22, 27, 29] (lob = 19 %; net = 18 %) [22, 24, 27, 29]. On the other hand, female players played a higher percentage of shots from the backcourt [22, 29] (clear = 23 %; drop = 17 %) [22, 24, 29]. Both sexes played more offensive strokes than defensive strokes [30]. To pursue an offensive strategy, more singles players preferred to serve low–short [27, 32, 33] by using a flat and short trajectory rather than a long and rising trajectory towards the back of the opponent's court. This allows an offensive stroke from the receiver to be avoided.

Successful players made fewer forced or unforced errors under both scoring systems [15, 18, 23, 26–28] (see Table 4). The number of unforced errors affects the final result [15, 23, 27]. No significant difference was found for notational parameters under the new system compared with the old system [23, 24]. The new scoring system results in a significant decrease in the average overall match duration and a significant increase in the average number of shots per rally compared with the old scoring system. With the adoption of the new scoring system, the game has become more offensive, as revealed by the way points end more often with a smash than under the old system [18].

Finally, the characteristic timing of events in a badminton match consist of actions of short duration and high intensity interspersed by short rest periods. Indeed, a typical match consists of an average rally time of 7 s and an average resting time of 15 s, with an effective playing time of 31 %.

3 Anthropometry

In several competitive games, technical skill, anthropometry and the physical performance capacity of individual players were the most important characteristics [34–36]. Anthropometric measurements sometimes revealed a correlation between body structure, bone mass [37, 38], physical characteristics and sporting abilities [39–44],

Table 2 Distribution of the different shots of a badminton game

Study	Subject (*n*)/condition	Clear	Smash	Drop	Drive	Lift/lob	Net	Push
Males								
Old scoring[b]								
Lee et al. [29]	International (40)/R	12.1	14.2	13.2	NS	19.6	20.7	6.1
Ming et al. [24]	Young national (16)/R	14	14	13	NS	23	17	10
New scoring[c]								
Abian-Vincen et al. [22]	Olympic Games (20)/R	NS	29.1 ± 8.4	3.8 ± 3.5	6.3 ± 3.9	NS	NS	NS
Abián et al. [26]	Olympic Games (20)/R/2008	NS	29.09 ± 8.43	NS	NS	2.31 ± 1.74	16.03 ± 6.6	NS
	Olympic Games (20)/R/2012		27.84 ± 8.14	NS	NS	3.92 ± 4.31	13.32 ± 5.38	NS
Tong et al. [27][a]	International (11)/R	13	14	16	15	12	17	14
Ming et al. [24]	Young national (16)/R	16	13	13	NS	22	17	13
Females								
Old scoring[b]								
Lee et al. [29]	International (40)/R	23.3	8.4	19.9	NS	20.2	16.6	4.1
Ming et al. [24]	Young national (16)/R	23	10	17	NS	15	15	11
New scoring[c]								
Abian-Vincen et al. [22]	Olympic Games (20)/R	NS	21.6 ± 9.5	9.0 ± 6.0	2.0 ± 2.7	NS	NS	NS
Ming et al. [24]	Young national (16)/R	23	8	22	NS	14	14	12

Data are expressed as % ±SD

R real match, *NS* not specified, *SD* standard deviation

[a] Converted as a percentage from absolute values of the article

[b] Old scoring (match-game 15 points for males and 11 points for females)

[c] New scoring (match-game 21 points for both)

Table 3 Distribution results of the percentage of distribution of the six effectiveness categories of a badminton game

Study	Subject (*n*)/condition	Fore-left	Fore-right	Mid-left	Mid-central	Mid-right	Rear-left	Rear-central	Rear-right
Males									
Lee et al. [29]	International (40)/R	24.2	23.4	6.0	2.1	4.7	17.4	2.0	19.9
Tong et al. [27]	International (11)/R	18[a]	18[a]	16[a]	NS	15[a]	16[a]	NS	17[a]
Oswald [30]	International (80)/R	11.7	11.8	26.0	NS	23.8	12.8	NS	14.0
Females									
Lee et al. [29]	International (40)/R	21.9	19.8	3.8	0.2	2.3	25.0	0.4	26.3

Data are expressed as % ±SD

R real match, *NS* not specified, *SD* standard deviation

[a] Converted as a percentage from absolute values of the article

Table 4 Comparative results of the different ways to win the point in a game of badminton

Study	Subject (*n*)/condition	Unconditional winner	Conditional winner	Forced failure	Unforced failure
Old scoring[a]					
Tong et al. [27]	International (11)/R	22.70 ± 7.75	0.50 ± 0.85	9.30 ± 3.59	21.20 ± 10.27
Chen et al. [23]	International (10)/S	36	1	50	13
		22	1	62	15
New scoring[b]					
Abian-Vincen et al. [22]	Olympic Games (10)/R/Men	NS	NS	NS	41.0 ± 9.4
	Olympic Games (10)/R/Women	NS	NS	NS	48.6 ± 9.0
Abián et al. [26]	Olympic Games (20)/R/2008	NS	NS	NS	41.01 ± 9.46
	Olympic Games (20)/R/2012	NS	NS	NS	42.64 ± 8.89
Chen et al. [23]	International (5)/S/Winner	33	2	55	10
	International (5)/S/Loser	20	1	68	11

Data are expressed as % ±SD

R real match, *S* simulated match, *NS* not specified, *SD* standard deviation

[a] Old scoring (match-game 15 points for males and 11 points for females)

[b] New scoring (match-game 21 points for both)

suggesting the possibility of assessing performance [45] on the basis of physical and anthropometric characteristics [46]. Body constitution similarities increase proportionally through different training levels among athletes practicing the same sport and discipline [47].

3.1 General Anthropometric Characteristics in Badminton Players

Anthropometric measures are often used to distinguish players according to their age or level of expertise. Most studies of anthropometry among badminton players are unable to distinguish singles players from doubles players [48–56], suggesting that general anthropometric characteristics are not crucial for understanding differences between these events. However, when considering height, this variable appears to distinguish the level of expertise. Indeed, one study [48] shows that the top 13 male competitors according to the world ranking (2008) are generally taller (+5 cm) than the studied population of lower-level badminton players, suggesting that being tall is an advantage, probably by increasing the percentage of situations in which an attack shot can be used. However, the literature also reveals slight differences [57] in the anthropometric characteristics in badminton players depending on the country of origin: international Nigerian [49], Malaysian [34, 54, 55, 58, 59], Indonesian [50], Turkish [51] and Spanish [60] players (see Table 5) are shorter (mean 171 cm) compared with the top 13 competitors [22, 34, 49, 54, 55, 58–61], while Danish [62], Czech Republic [48, 63], South African [64, 65] and German [66, 67] badminton players are taller (mean 182 cm).

As for weight, several studies show differences in race. It would appear that, in the top 13 male competitors [48] (mean 70 kg, 179 cm), international badminton players are not very similar in terms of weight (mean 67 kg) and stature (mean 174 cm). For instance, Lee et al. [57] showed a difference between Asian, African American, White and

Table 5 Summary of studies reporting anthropometric characteristics of badminton players

Study	Subjects (*n*)	Height (cm)	Mass (kg)	% Fat	BMI	Endomorph	Mesomorph	Ectomorph
Males								
Mathur et al. [49]	Elite (131)	172.4 ± 5.3	67.9 ± 3.6	8.2 ± 1.7[b]	NS	2.2 ± 0.9	3.9 ± 1.1	2.9 ± 0.6
Poliszczuk and Mosakowska [48]	Elite (9)	184.63 ± 6.01	80.71 ± 9.05	9.59 ± 3.31[NS]	23.60 ± 1.96	3.0 ± NS	3.0 ± NS	2.5 ± NS
Rahmawati et al. [50]	Elite (19)	160.4 ± 6.78	48.7 ± 7.38	NS	18.9 ± 2.05	3.29 ± 0.76	3.70 ± 1.08	3.67 ± 1.25
Revan et al. [51]	Elite (50)	166.4 ± 5.6	59.5 ± 7.7	22.8 ± 3.8[NS]	21.5 ± 2.7	3.5 ± 1.0	2.1 ± 1.2	2.8 ± 1.4
Abián-Vicén et al. [60]	Elite (46)	177.94 ± 6.00	71.65 ± 5.70	8.35 ± 1.44[a]	NS	2.25 ± 0.58	3.74 ± 0.90	2.83 ± 0.91
Singh et al. [70]	Sub-elite (50)	NS	NS	NS	NS	2.66 ± 1.98	3.17 ± 1.11	3.26 ± 1.18
Raschka et al. [66]	Sub-elite (40)	182.0 ± 4.6	77.5 ± 5.9	10.8 ± 1.9[NS]	23.4 ± 1.6	2.3 ± 0.6	3.2 ± 0.9	2.7 ± 0.8
Carter et al. [46]	Junior (7)	NS	NS	NS	NS	2.5 ± NS	4.6 ± NS	3.2 ± NS
Álvarez et al. [52]	Junior (19)	170.80 ± 11.23	61.10 ± 16.66	12.03 ± 2.83[a]	20.56 ± 3.39	2.49 ± 0.53	4.14 ± 0.86	3.58 ± 1.17
Hussain [71]	Junior (30)	165.5 ± 5.3	63.5 ± 4.9	11.4 ± 1.3[a]	NS	3.0 ± 0.52	4.1 ± 0.78	2.5 ± 0.64
Females								
Revan et al. [51]	Elite (50)	164.2 ± 7.3	60.1 ± 7.3	23.7 ± 3.9[NS]	22.3 ± 2.2	3.7 ± 1.0	3.1 ± 1.2	2.3 ± 1.1
Abián-Vicén et al. [60][b]	Elite (46)	165.37 ± 5.64	61.10 ± 3.91	16.91 ± 2.36[a]	NS	3.44 ± 0.53	3.66 ± 0.95	2.17 ± 0.72
Álvarez et al. [52]	Junior (19)	165.38 ± 3.63	59.27 ± 5.21	15.52 ± 3.07[a]	21.63 ± 1.25	4.17 ± 1.18	2.59 ± 0.56	2.59 ± 0.56

Data are expressed as mean ± SD. Anthropometric values are expressed as mean ± SD

BMI body mass index, *NS* not specified, *SD* standard deviation

[a] Estimated body fat percentage according to the sum of four skinfolds (triceps, suprailiac, subscapular and abdominal)

[b] Estimated body fat percentage according to the sum of nine skinfolds (triceps, subscapular, suprailiac, thigh and calf skinfolds, bi-epicondylar diameter of the femur and humerus, and flexed biceps and calf girths)

Hispanic populations. When comparing international players by continent, the White population [22, 48, 60, 62, 63, 67] had the highest values (mean 74 kg, 180 cm), whereas the African population [49, 64, 65] had intermediate values (mean 70 kg, 176 cm), nearest the top 13 male competitors, and the Asian population [34, 50, 51, 54, 55, 59] had the lowest values (mean 60 kg, 167 cm).

Body fat is assessed in several studies independent of the country (see Table 5), using various measurement methods such as the Harpenden skinfold [68] and the body composition analyzer [69]. The average of all studies reveals 11.34 % fat [22, 34, 46, 48–55, 59–67, 70–72]. When focusing on the level of expertise, mean values are 12.85 % in elite males, 10.15 % in sub-elite males, 9.84 % in junior males, 18.41 % in elite females and 14.11 % in junior females. Badminton players are generally lean [63] (mean 11–12 %), as shown in 10 of 24 studies in which players were leaner than 12 %, suggesting that leanness would be advantageous with regard to the game's high intensity. Only Malaysians [68, 73] (14.6 ± 1.7 %) and Turks [51] (22.8 ± 3.8 %) have a higher percentage of fat than average, and Nigerians [49] (8.2 ± 1.7 %), Czechs [63] (8.3 ± 2.6) and Spaniards [60] (8.4 ± 1.4) have a lower percentage. In 1997, Majumdar et al. [61] investigated the percentage of fat in the best players (mean 12.1 ± 3.4 %). Furthermore, the body mass index of badminton players (ranging from 18.9 ± 2.05 to 23.6 ± 1.96) showed a normal weight [61, 62] (mean 22–23). The top players' anthropometric characteristics appeared to increase by approximately 5 cm and 5 kg between 1997 [61] and 2008 [48]. However, this could be due to the difference in the method used, either by Harpenden skinfold with a different number of sites or by body impedance assessment (opposition to the flow of an electric current through body tissues to estimate fat-free body mass and body fat).

Few studies have examined the length and circumference of the arm and the legs which could be useful in the ability to cover the court [66, 74, 75]. They suggest that a large leg circumference could be useful for jumping during badminton play and the badminton player's continuous movement on the toes in a small area [75].

3.2 Badminton Players' Somatotype

The somatotype measurement is an indication of a person's general build based on Sheldon's system [76]. Three components of the somatotype include the individual's relative fat (endomorphy), musculoskeletal robustness (mesomorphy), and linearity (ectomorphy). The highest values give an indication of the general shape [64]. It can demonstrate similarities and differences in several groups

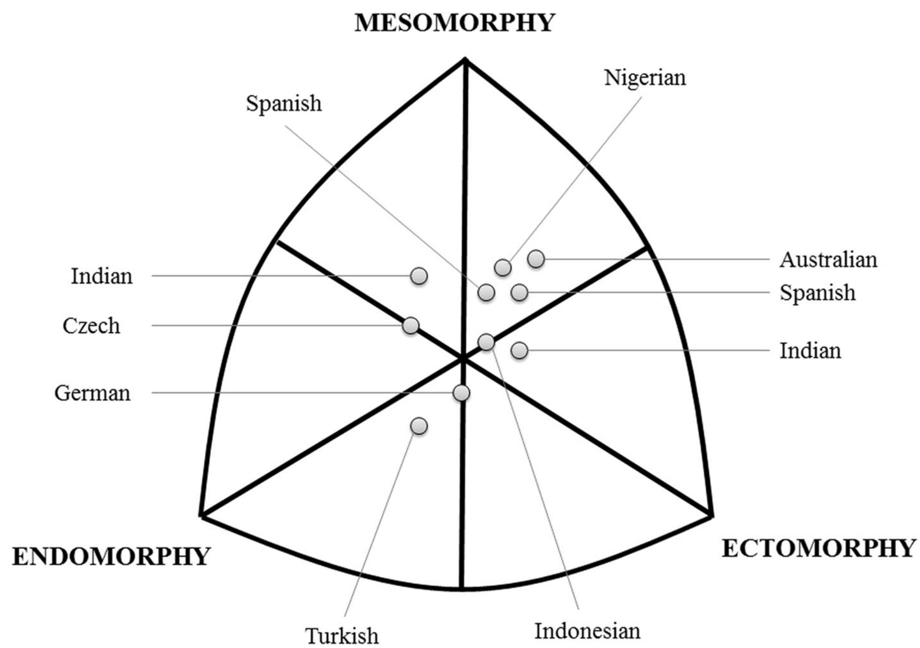

Fig. 1 Average male somatotype of badminton depicted on the Heath-Carter somatochart [46]

within the same sport. Badminton players showed a mixed somatotype (see Fig. 1), with a mean value of 2.8 on endomorphy, 3.6 on mesomorphy and 3.1 on ectomorphy.

More specifically, several studies found an ectomesomorphic profile (see Table 5) in Australian players [46] (2.5-4.6-3.2), Spanish players [52, 60] (2.3-3.7-2.8 and 2.5-4.1-3.6) and Nigerian players [49] (2.2-3.9-2.9). One study found an endomesomorphic profile in Indian players [71] (3.0-4.1-2.5) and another found endoectomorphic values in Turkish players [51] (3.5-2.1-2.8). Czech players [48] (3.0-3.0-2.5), German (2.3-3.2-2.7), Indonesian [50] (3.3-3.7-3.7) and Indian players [70] (2.7-3.2-3.3) had a homogeneous profile. However, all of these values are located near the middle of the somatochart, falling into the 'central' somatotype category (see Fig. 1). This suggests that tall, lean, muscular players are suited to match characteristics. This is shown by high values in their mesomorphic and ectomorphic components, and low values in their endomorphic component [70].

All these studies tended to show that badminton players are generally tall and lean, with an ectomesomorphic body type suited to the high physiological demands of a match.

4 The Physiology of Badminton

Badminton is an extremely demanding sport [20, 77]; in fact, it is the most gruelling racket sport in the world [78, 79]. Players are required to move quickly when necessary, changing direction in the game due to the nature of the movements required during a rally [64, 77, 80]. Elite players need to perform at their maximum limits of speed, agility, flexibility, endurance and strength [77]. Badminton is a combination of high-intensity short rallies (anaerobic system) [74] and longer, moderate- or high-intensity rallies (aerobic system) [61, 79] sustaining efforts and promoting recovery between rallies [39]. Singles are more demanding than doubles [79], with approximately 80 % of rallies lasting less than 10 s [15, 20, 22, 25, 79, 81].

4.1 Aerobic and Anaerobic Systems in Badminton

Badminton player efforts are intermittent in nature and place high demands on both the aerobic and anaerobic systems for delivery during play and recovery [82]. Researchers have observed that 60–70 % of the energy yield during games is derived from the aerobic system, while 30 % is obtained from the anaerobic system [21, 64, 83], with a great demand on the alactic anaerobic system [15] and, to a lesser degree, the lactic anaerobic metabolism [15].

The high frequency and intensity of play during a match, with the high maximum and average heart rates (HRs), indicate that badminton demands a high percentage of individual aerobic power [15, 20, 25, 84]. Singles badminton may place more complex demands on the body's energy systems since matches require a sufficient aerobic capacity to produce energy and facilitate recovery from anaerobic exercise [79]. Specific aerobic and anaerobic exercises for badminton [84] are needed to improve physiological variables [63, 77, 85]. The quality of the athletes' sport performance reduces the experience of fatigue [32] in a match and the risk of lower-limb injuries [86]; therefore, a correct badminton training approach should consider the development of these different energy systems [20].

4.2 Physiological Badminton Tests

4.2.1 General Tests

Laboratory and field test methodologies and procedures differ among researchers engaged in badminton science. The extent to which dissimilar approaches to badminton exercise research affects the validity of the findings remains unanswered. The identification of participants' maximal oxygen uptake (VO_{2max}) was performed using either a treadmill [25, 33, 63], with a graded exercise protocol on a bicycle ergometer [87], or a multistage fitness test [59, 79, 88]. Yo-Yo intermittent test variations are thought to be another valid measure of intermittent field sport endurance [89].

4.2.2 Specific Tests

Various studies have addressed the validity of a limited range of specific tests to determine the physiological capacity and performance of elite badminton players [21, 84, 90–92]. In order to reproduce the ecological situation as faithfully as possible, field tests were performed on a badminton court. The classical test consists of six light-bulbs mounted on posts with the lights connected to a programming device [93]. Pairs of lights were located on the fore-, mid- and backcourt [21, 33, 94]. Players were required to respond to each flash by moving into the respective corner. For the forecourt and midcourt light flashes, the subjects performed a front and side lunge. For the backcourt, they imitated a backward jump smash between the court lines. Testing started with 15 flashes/min and the intensity was increased by three flashes/min every 3 min [21, 94].

The sideways agility test required the players to shuffle laterally across the width of the court for a total of ten repetitions, and to strike each of the upturned shuttlecocks placed on the line marking the outside of the single's court. The four-corner agility test required the players to move around the four corners of the court for a total of 16 repetitions, in an ordered sequence of four directions, and to strike each of the upturned shuttlecocks located at each corner [59]. Blood lactate, oxygen uptake (VO_2) and HR were continually recorded before [15, 20, 23], during [15, 20, 21, 23, 95] and after the test [15, 20, 21, 23].

4.3 Physiological Characteristics of Badminton Players

Several studies specifically focused on oxygen deficit, HR, blood lactate, and physiological demands during real or simulated matches, and during test performance [15, 20, 25, 83, 90, 96–100]. Table 6 summarizes the physiological responses for male and female badminton player regardless of level or condition.

4.3.1 Maximal Oxygen Uptake and Metabolic Thresholds

VO_{2max} is said to be set by metabolic and oxygen transport limits or a combination of both [101, 102]. To some extent, it appears that depressed VO_{2max} values may be indicative of fatigue or overtraining rather than actual training progress [101]. Singles players had greater predicted VO_{2max} than doubles players (50.6 vs. 45.5 mL/kg/min) [103].

Considering the average from all studies, VO_{2max} of male players was 56.1 mL/kg/min, and 47.2 mL/kg/min of female players. When considering the expertise level, the mean value was 56.3 mL/kg/min in elite males, 55.1 mL/kg/min in sub-elite males, 57.2 mL/kg/min in junior males, 45.8 mL/kg/min in elite females and 48.1 mL/kg/min in junior females (see Table 6).

4.3.2 Heart Rate

The maximum and average HR [104] were recorded every 5 s throughout the match by a telemetry pulsometer [15, 20, 23, 28, 58, 63, 79, 82, 94, 105, 106]. Data was also recorded by a written ECG.

The high maximal HR (HR_{max}) sustained throughout the game depicts considerable stress on the cardiovascular system [61]. The literature reports an average HR_{max} value of 191.0 beats/min in males and 197.6 beats/min in females. When considering the expertise level, the mean value is 188.0 beats/min in elite males, 194.0 beats/min in sub-elite males, 198.7 beats/min in junior males, 193.4 beats/min in elite females and 202.5 beats/min in junior females (see Table 6).

Elite badminton players are expected to possess the skills and techniques necessary to elicit the greatest possible strain on their physiological systems [79, 105, 107]. They may frequently exercise at a HR beyond their anaerobic threshold [79]. The average HR in both males and females was over 90 % of the HR_{max} [20, 23, 25, 58, 61, 87, 108], or 170–180 beats/min [21, 109–111]. The average HR appears to be linked to the level of players with values of 194.0 beats/min in sub-elite versus 188.0 beats/min in elite players. Studies showed that the HR_{max} is independent of strokes performed, with values between 90 and 94 % [33, 85, 87].

4.3.3 Blood Lactate Responses

The lactate concentration was analyzed by means of blood samples taken from the earlobe on BM-Lactate reactive

Table 6 Physical mean laboratory values

Study	Subject (n)	Condition	Lactate (mmol/L)	VO_2 (mL/kg/min)	VO_{2max} (%)	Mean HR (beats/min)	HR_{max} (beats/min)
Males							
Cabello Manrique et al. [15]	Elite (11)	Tournament	3.79 ± 0.91	NS	NS	173.43 ± 8.86	190.57 ± 5.50
Cabello et al. [20]	Elite (41)	Tournament	3.9 ± 2.2	NS	NS	172 ± 10	191 ± 9
Faude et al. [25]	Elite (4)	Simulated match	1.9 ± 0.1	46.0 ± 4.5	74.8 ± 5.3	166 ± 6	NS
Docherty [108]	Elite (42)	Simulated match	NS	NS	NS	NS	175 ± 6
Liddle et al. [79]	Elite (10)	Simulated match	NS	NS	54.5 ± 2.5	NS	192.6 ± 7.5
Chen et al. [95]	Elite (14)	Training	NS	52.4 ± 4.1	NS	NS	186 ± 5.4
Chin et al. [21]	Elite (12)	Physical test	10.4 ± 2.9	NS	NS	NS	187 ± 8
Andersen et al. [82]	Elite (35)	Physical test	NS	63 ± 0.8	NS	NS	188 ± 1
Heller [63]	Elite (54)	Physical test	10.6 ± 2.4	63.2 ± 3.7	NS	NS	186.6 ± 9.2
Ooi et al. [59]	Elite (12)	Physical test	NS	56.9 ± 3.7	NS	NS	NS
Wonisch et al. [84]	Elite (17)	Physical test	7.6 ± 2.1	NS	NS	NS	195 ± 6
Chen et al. [23]	Sub-elite (10)	Simulated match	4.6 ± 0.4	NS	NS	178.9 ± 1.8	NS
Ghosh [87]	Sub-elite (8)	Simulated match	12.2 ± 2.1	57.4 ± 7.0	NS	NS	197.0 ± 6.7
Majumdar et al. [61]	Sub-elite (6)	Simulated match	4.7 ± 1.9	55.7 ± 4.4	NS	157 ± 11	183 ± 9
Bottoms et al. [33]	Sub-elite (9)	Physical test	NS	52.1 ± 10.9	NS	NS	200 ± 11
Lin et al. [106]	Sub-elite (10)	Physical test	NS	51 ± 6	NS	NS	196 ± 5
Ooi et al. [59]	Sub-elite (12)	Physical test	NS	59.5 ± 5.2	NS	NS	NS
Gowitzke et al. [213]	Junior (10)	Physical test	9.49 ± NS	56.34 ± NS	NS	NS	202.4 ± NS
Heller [63]	Junior (50)	Physical test	12.0 ± 1.7	64.6 ± .4	NS	NS	194.9 ± 7.7
Van Lieshout [64]	Junior (8)	Physical test	NS	50.7 ± 3.0	NS	NS	NS
Singh [107]	Junior (25)	Physical test	NS	NS	35.8 ± 5.6	NS	NS
		Physical test	NS	NS	47.2 ± 5	NS	NS
Females							
Cabello et al. [20]	Elite (38)	Tournament	2.4 ± 1.0	NS	NS	176 ± 10	193 ± 9
Faude et al. [25]	Elite (8)	Simulated match	1.9 ± 0.9	36.4 ± 2.8	72.6 ± 7.2	170 ± 10	NS
Ooi et al. [58]	Elite (1)	Simulated match	5.8 ± NS	NS	NS	172 ± NS	NS
Heller [63]	Elite (26)	Physical test	11.5 ± 2.0	55.2 ± 2.6	NS	NS	193.8 ± 7.9
Gowitzke et al. [213]	Junior (6)	Physical test	8.98 ± NS	47.28 ± NS	NS	NS	201.3 ± NS
Heller [63]	Junior (26)	Physical test	11.7 ± 1.6	54.9 ± 2.5	NS	NS	203.7 ± 7.8
Van Lieshout [64]	Junior (7)	Physical test	NS	42.0 ± 2.8	NS	NS	NS

Data are expressed as mean ± SD

HR heart rate, HR_{max} maximal heart rate, VO_2 oxygen uptake, VO_{2max} maximal oxygen uptake, *NS* not specified, *SD* standard deviation

strips, and analyzed immediately using the lactate-mediator oxidase color reaction technique and Accusport® reflection photometer [112, 113]. This recording was carried out at rest, at the end of the match, and at 1-, 3-, 5- and 10-min intervals [15, 20, 21, 23, 63, 106]. Lactate concentration was also analyzed by capillary whole-blood samples (20 µl) [25, 58, 94].

Studies show that in singles matches, badminton blood lactate ranges from 2.9 to 12.2 mmol/L, with a mean value of 4.4 mmol/L [15, 20, 23, 61, 62]. Badminton players play at a high percentage of their VO_{2max}, or very close to maximum HR. Moreover, a moderate energy yield comes from the anaerobic lactic acid system [87]. Considering the average from all studies, maximum lactate concentration for male players was 7.0 mmol/L, and 7.1 mmol/L for females. When focusing on the level of expertise, the mean value was 5.87 mmol/L in elite males, 7.16 mmol/L in sub-elite males, 10.8 mmol/L in junior males, 5.4 mmol/L in elite females and 10.3 mmol/L in junior females. These differences may be explained by the differences in age, fitness, and training levels of the subjects [15]. These low values may also be due to a greater aerobic work capacity conditioned by a higher degree of previous training [15, 21, 114], carbohydrate ingestion to prevent performance deterioration [33], and myoglobin, which can act as a short-term supplier of oxygen, particularly at the onset of activity [61, 114]. Moreover, this could also be explained by the time at which the blood lactate is taken (at the end of the match) and may not reflect the peak, which would be expected to occur during the match [20, 83].

4.4 Speed, Agility, Strength, Flexibility and Muscular Endurance

Several factors contribute to success in this sport, including technique and tactics [21]. Badminton players need great physical ability, especially agility, aerobic strength and explosive power [74], in order to perform efficiently. To improve performance, it is important to identify the specific traits and parameters that contribute to playing ability [74].

Performance is determined by the relationship of speed, agility, flexibility, shoulder strength, explosive strength and muscular endurance [5, 39, 74, 80, 115–120] which show a significant relationship with playing ability. For instance, Tiwari et al. [80] showed a significant correlation in sub-elite players between these qualities and player ability (r ranged from 0.55 'explosive strength' to 0.83 'agility'). Flexibility is the ability to move the body and its parts through as wide a range of motion as possible without undue strain on the joints and muscle attachments [80, 121]. Explosive strength ($r = 0.55$) is the product of speed and strength; it is the ability of a muscular unit or combination of muscular units to apply maximum force in minimum time [80]. Speed ($r = 0.67$) is a limb's quickness of movement; it is a part of badminton [80]. Shoulder strength ($r = 0.69$) is a muscle's ability to overcome resistance to perform a shot [80]. Muscular endurance ($r = 0.75$) is the ability of a muscle or a group of muscles to perform repetitive contraction over a period of time [80]. Agility ($r = 0.83$) is the ability to change the body's direction; the player uses different types of movement during a match [80, 121].

4.5 Dehydration in Badminton Players

Total sweat loss was estimated using the difference between pre- and post-body weight divided by the individual's body surface area, and was expressed as kg/m/h [17, 19, 95, 122]. The physiological demand is determined largely by the surface area, equipment, projectile characteristics, extent to which the game is contested, and by environmental factors such as temperature [95, 123] and humidity [17, 81]. Players can modify the physiological demands by controlling the rest intervals between rallies and between games and sets [81]. A major determinant of the game's outcome is an individual's physical fitness, which can be influenced by hydration and nutritional status [17, 19, 81, 122]. Badminton players have many opportunities to rehydrate during play due to the intervals between points and sets [81].

The average sweat rate during a badminton game was 1.11 L/h [17, 19, 122]. Thus, dehydration was 0.47 ± 1.03 % after the second round and 0.23 ± 0.43 % after the quarter-finals [122]. In addition, badminton players correctly rehydrated during badminton matches and between rounds, based on stable body mass values during the tournament. After the match, urine analyses showed proteinuria, an increase in the presence of nitrites (mean pre 4.1 mg n/L; post 49.2 mg n/L), glycosuria (mean pre 0.0 mg/dL; post 8.7 mg/dL), ketone bodies (mean pre 4.3 mg/dL; 9.4 post mg/dL), erythrocytes (mean pre 3.3 erythrocytes/μL; post 14.7 erythrocytes/μL) and leukocyturia (mean pre 2.6 leukocytes/mL; post 49.3 leukocytes/mL) produced primarily by the high intensity of the game [17, 122]. Similar urinary anomalies have been observed in sports of longer duration, such as the half marathon or marathon [17]. Last, the low level of dehydration reached during a badminton game did not affect muscle performance [19] but could be prejudicial in a long tournament [17].

4.6 Summary

The intermittent actions during a game are demanding on both the aerobic and anaerobic systems: 60–70 % on the aerobic system and approximately 30 % on the anaerobic system, with greater demand on the alactic metabolism with respect to the lactic anaerobic metabolism. This sport is highly demanding, with an average HR of over 90 % of the player's HR_{max} and a mean value of blood lactate of 4.4 mmol/L.

5 Visual Fitness

Racket sports require athletes to process information in a time-constrained environment [124]. Anticipating actions is a crucial ability, particularly where uncertainty and spatiotemporal constraints are significant [125]. In behavioral studies of anticipatory skill in sports, elite players are consistently able to use early information from an opposing player's body kinematics [126–129]. Several research studies have examined brain function, information processing and decision procedures.

5.1 Brain Function in Badminton Players

Some studies have investigated brain function in badminton players. Players were asked to watch videos [130] or images [131, 132] while their brain activity was continuously recorded via functional magnetic resonance imaging (fMRI). The observation of body movements and the anticipation of shuttlecock trajectories activated several networks of brain areas [130, 131, 133–137].

In a sport with an anticipation task, elite players showed stronger fMRI activations than novices in brain areas associated with visual attention and the analysis of body kinematics [131]. There is a strong link between action, observation and attention. Players' intentional movements can be an environmental cue for the direction of attention [131]. Elite players showed enhanced activation in frontal regions, especially for early parts of the action sequence [130, 132]. This acts as a relay, passing information from visual-processing areas to motor-processing areas, regions that support visuomotor coordination [138, 139]. As a result, badminton athletes have higher visuomotor skills than individuals not playing racket sports [132]. The bilateral cortical network is a key region supporting the anticipation task relative to control stimuli [130, 131, 133]. Badminton players appear to have highly developed sensory-motor programmed activities [140].

Fine motor dexterity of the hands is necessary for elite badminton skills [132] by using coordination of small muscle movements, such as the fingers in coordination with the eyes. Few studies have analyzed badminton players' ability to cope with the neural [141] and biomechanical constraints of gripping and swinging a badminton racket [142].

5.2 Visual Reaction Time

Visual reaction time is the time required to respond to visual stimuli. It can be divided into three parts: simple reaction time (one stimulus–one response), recognition reaction time (one stimulus–response or not) and choice reaction time (multiple stimuli–multiple responses) [143]. Badminton players used the visual search strategy to respond briefly and produce greater speed, accuracy and precision of movement [144, 145]. Badminton players' range of vision is relatively great, amounting to, on average, 172.9°, with higher values for the left eye compared with the right eye (+7°) for all right-handedness and left-eye dominance [145]. More adequate responses and a shorter response time were noted in the right visual field [146]. A stimulus perceived with the right eye is processed in the left brain hemisphere, which simultaneously controls function of the right side of the body (arm and upper limb), resulting in a quick and accurate response [145]. The elite badminton players evaluated reacted more rapidly to visual stimulus than intermediate players during a target pointing task [147].

During reaction to visual and auditory stimuli, studies showed that elite players required a shorter reaction time than non-players [143, 147, 148]. This ability showed a significant correlation during an ecological task with a more rapid reaction to a visual stimulus. Studies showed that elite players had a quicker reaction time and a more precise reaction than players of lower skill [138, 143, 144]. They used more time concentration on the visual cue [144] and required refined hand-eye coordination and visuospatial ability [149, 150]. To improve badminton players' ability to predict and anticipate the trajectory of the shot that their opponent will produce, researchers used video simulation [151, 152], sound processing systems [151] and specifically designed badminton software [153]. Two ways are used to increase perceptual abilities: first, by practicing certain tasks on the court against a stronger opponent [152]; and second, by supplementing normal training through perceptual training based on video demonstrations [152, 153]. With any experience, specific improvement and capabilities may develop in the visual system [154, 155], especially for anticipatory skills in novices [156]. Overall, the use of a visual-based training method facilitates the acquisition of perceptual expertise, allowing athletes to train and improve off-court, in a self-paced manner [153]. The ability to react to a visual stimulus could be a factor for reaching higher performance levels [147].

5.3 How Badminton Players Obtain Information and Make Decisions

Several studies in psychology have agreed on the ability to anticipate the shuttlecock flight path before racket contact. This is a critical factor for successful performance [157]. Elite players were able to pick up more relevant information from earlier display cues than novices [155, 158, 159]. To predict in advance the direction and force of an opponent's stroke, badminton players used information from postural cues before the stroke [157]. They should have better coincidence-anticipation timing accuracy when the time for anticipation is limited or when the task requires faster response [160].

Several studies presented each stroke under four conditions varying in terms of the time course of information available. The participants viewed either film or point-light displays under a range of temporal or spatial occlusion conditions [126, 155, 157, 158, 161]. In the most difficult condition (t1), the players were permitted to view the opponent's hitting action until just 167 ms before racket–shuttle contact. In the other conditions, the display was occluded 83 ms before contact (t2), at the contact point (t3), 83 ms after contact (t4), and following the last outward flight of the shuttle (t5) [126, 155, 157, 158, 161]. Regardless of the player's level, information could be picked up at t1 [125, 161]. For elite players, information pick-up prior to t1 appeared to be attributable to attunement to the kinematics of both the upper and lower body [126]. This result differs from that reported by Abernethy and Russell [158], who stated that no information pick-up was possible at t1 [156]. Concurrent vision of arm motion improved elite players' directional prediction. The addition of vision of the lower body kinematics facilitated prediction accuracy based on racket arm and upper-body kinematics [161]. The elite players used preferentially linked upper-body kinematics based on the upper body, arm and racket to improve prediction [126, 156, 158, 161]. For non-elite players, whatever information pick-up occurred prior to t1 appeared attributable simply to sensitivity to the isolated kinematics of the upper body.

Information pick-up in the period from t2 to t3 by elite players was apparently due to their attunement to information contained specifically within the racket kinematics and the lower body [126, 158, 161]. For non-elite players, the arm appeared to provide beneficial referential information for the racket [126, 158, 161].

The perceptual strategies of elite performers were to extract pertinent information from a spatial cue [158]. For them, both the racket and the arm holding it contributed to the anticipation of the opponent's stroke [157, 158]. The prediction performance of elite players was superior to that of novices at all points, with the exception of t1 and t5 [157, 161]. Better badminton players have a greater ability to anticipate stroke outcome from early postural cues [157].

5.4 Summary

Badminton players are visually fit, picking up accurate visual information in a short time. To have an efficient anticipatory behavior, elite players are consistently able to use early information from an opposing player's body kinematics.

6 Biomechanics

Studies have been performed to analyze the movement of the players and the shuttlecock [162, 163]. Intersegmental coordination in complex, forceful movements has been discussed in the biomechanics literature [164]. Badminton requires jumps, lunges and quick changes in direction, especially the high frequency of 'stop-and-go' manoeuvres [165–167] and rapid arm movement from a wide variety of postural positions [13, 14]. The use of high-speed cameras [168–170] or other scientific instruments [170–172] reveals details of performance.

6.1 Shuttlecock Aerodynamics

The aerodynamic force applied to the badminton shuttlecock at high speed is approximately 50 times greater than gravitational force at high speed, proving that this sport is highly constrained by aerodynamics. When falling vertically, the shuttlecock achieves 99 % of its terminal velocity 1.84 s after falling 9.2 m, with a terminal velocity of 6.80 m s^{-1} [173–177].

The shuttlecock generates significant aerodynamic drag and an atypical and surprising flight trajectory [11, 12], with an asymmetric curve [175] different from a ball's trajectory [178] characterized by an aerodynamic wall [175] that occurs when the ratio of the velocity of launching speed on the terminal velocity is high (ratio: 17.5 for badminton). The in-flight deceleration is the greatest of any airborne sporting projectile [173, 174] due to the high drag aerodynamic coefficient which is proportional to the square of shuttlecock velocity, air density and the undeformed projected frontal area of the shuttlecock. The average drag coefficient for shuttlecocks is between 0.5 and 0.6 [11, 175, 179, 180]. The flight dynamic is also affected by the deformation of the shuttlecock skirt [181, 182]. During a smash stroke, the shuttlecock velocity increases linearly with skill level from approximately 30 m s^{-1} in untrained players to approximately 70 m s^{-1} in elite players [183].

A wide variety of shuttlecocks are available commercially. Traditionally, shuttlecocks can be divided into two categories: feather shuttlecocks and synthetic shuttlecocks [180, 184], with different aerodynamic properties. Natural feather shuttlecocks have lower drag coefficients at low speeds and significantly high values at high speeds. Synthetic shuttlecocks show opposite trends. Synthetic shuttlecock trajectories have wider ranges than feather shuttlecocks of up to 10 % [184]. The end of the flight trajectory is steeper for feather shuttlecocks due to the significantly higher drag at high speeds [11, 175, 179, 185]. A stroke's angle and initial angle velocity influence trajectory [186].

6.2 Racket Dynamics

The racket is subjected to significant dynamic effects [1, 10, 187–191]. Racket deflection is due to high rotational and translational accelerations [1, 10, 187, 188]. It plays an important role in the transfer of momentum to the shuttlecock [1, 7, 9, 10, 187, 188]. Small differences in racket design have a great influence on dynamic properties [10, 192]. The simplified racket is composed of two uniform beam elements, representing the shaft and the head of the racket [10, 187]. Racket stiffness and mass properties likely influence the impact and restitution coefficient [187, 193, 194]. Technological innovations have had a great influence on rackets by making them light [8].

During the stroke, the racket is first swung backward and then forward before hitting the shuttlecock [10, 187, 195]. The backswing takes under 0.2 s, with a negative deflection of the racket being observed; the forward stroke lasts around 0.1 s, with a positive deflection [7, 10, 187]. To obtain maximum benefit from elastic deformation, impact should occur when racket deflection returns to zero (± 0.05 s), when tip velocity is highest [10, 187] and players are able to use racket elasticity to their advantage [191, 196].

Maximum deflection of the racket head (before impact) ranges from 38.5 to 56.2 mm [1], and maximum head velocity ranges from 35 to 50 m/s [1, 188–190, 193, 197]. Shuttlecock velocity depends on string tension; lower tension generates greater shuttlecock velocity than high tension [198]. At impact, average velocity (4.48 ± 0.20 to 1.67 ± 0.32 m/s) decreases as tension increases (10–13.6 kg) [198].

6.3 Kinematics Analysis

6.3.1 Lunge Performance in Badminton

Players employ lateral sidestepping and crossover stepping movements [199], with different levels of stride force [200], in order to move around the court. Lunging is an integral part of competitive athletes' movement repertoires [117, 201], representing 17.86 ± 4.83 % of movements performed during a singles match [201]. Lunging is determined by strength qualities (strength, flexibility, leg length) [117] and uses different techniques [201]. Players adapt the force generated during the lunging action to complete the movement successfully and to reduce excessive force [202].

Kinetics and kinematics between different lunge directions can provide biomechanical information on enhancing athletic performance [14] during a right-forward lunge [203]. Prevention, performance [204] and comfort are important functional design features for court shoes [205] due to the difference in plantar pressures among right-forward and left-forward lunges, and one-step jumps [206]. The external ground repulsion force and plantar pressure show that the left-forward lunge step induces greater ground reaction force and peak plantar pressure on the player's dominant leg compared with other lunge directions [14].

Footwear can influence performance and comfort during a lunge [207–211]. Forces tend to be directed towards the front and front lateral portion of the shoe on the racket side, and the lateral and rear lateral portion on the non-racket side [212].

6.3.2 Kinematic Analysis of Strokes

Several studies have researched and conceptualized power strokes, i.e. the clear and the smash [85, 213–226]. The muscular surface electromyography (EMG) pattern is similar between power strokes (smash and clear), but different from drop, [222] and reveals a proximal to distal sequence. Moreover, despite a similar kinematic pattern, the jump smash reveals a higher EMG activity of the upper limb in the phase before contact than the smash [227], allowing a slightly higher initial shuttle velocity (+3 %) [see Table 7]. Stroke contact duration time is similar (approximately 4 ms), and analysis of the kinetic chain highlights a greater angular velocity in the shoulder than in the elbow and the wrist [224].

To produce the power needed in these strokes with a minimum energy cost [221], players take advantage of adding velocity with a sequential proximo-distal joint action [7, 81, 164, 213–215, 228–234]. Coordination [235] produces the force from the ground to the lower limb [236–238] and to the upper limb [239]. First, the hip and intervertebral joints rotate, during the reverse hip rotation; the intervertebral joints may counter-rotate then reverse [85, 213–215, 228, 240, 241]. The upper arm commences a lateral rotation at the shoulder to the hitting direction [213–215, 218, 224, 228, 240, 242, 243]. In addition, elbow flexion and radio-ulnar supination begin [213–215, 228, 240]. Medial rotation at the shoulder starts, then the elbow [244, 245] and radio-ulnar activate [245] and radio-ulnar pronation occurs [213–215, 228, 240]. Forearm rotation [224, 246–248] emanated from pronation (forehand) and supination (backhand) [12, 172, 228, 239, 245], and players rarely used a 'wrist snap' [195, 240, 243, 246, 247].

Joint contribution made to the velocity of the shuttle during a smash can be attributed to 53 % of the final output to shoulder rotation and radio-ulnar pronation [240, 243]. All joint (wrist, elbow and shoulder) angles perform an important role in different types of strokes [6, 249]. The strokes exerted different muscular activity [250]. For Tsai et al. [250], the middle deltoid initiates the stroke (−441.25 ms) during a forehand smash. The major deltoid begins (−172.75 ms), followed by the triceps (−77.63 ms) and the wrist extensor (−63.38 ms). Finally, the biceps (−48.75 ms), wrist flexor (−43.50 ms) and posterior deltoid (−32.88 ms) are activated. Other studies [227, 230] found comparable sequences, with slight differences due to the number of electrodes on the experiment design and variability between players; the choice of sequencing and timing patterns [226, 251] may depend on individual skills [196] or preferences [164, 252]. The increase in angular velocity (see Table 8) of the body segments will be advantageous to perform strokes with greater shuttle velocity [226, 232, 249, 253, 254]. The power of the strokes depends on the values of angles and the angular velocities of joints [245].

Table 7 Biomechanical parameters of badminton athletes

Study	Stroke	Subject (*n*)	Shuttle velocity (m/s)	Shuttle angle[a] (°)	Contact height (cm)	Racket angle (°)
Males						
Jaitner et al. [234]	Jump smash	Elite (4)	65.0 ± 3.34	20.3 ± 4.36	288.0 ± 9.0	NS
Tsai et al. [221]	Jump smash	Elite (7)	67.9 ± NS	−13.47 ± NS	278 ± NS	NS
Lee [232]	Jump smash	Sub-elite (NS)	65.72 ± NS	NS	NS	NS
Tsai et al. [221]	Jump smash	Collegiate (7)	56.5 ± NS	−8.69 ± NS	264 ± NS	NS
Rambely et al. [190]	Smash	Elite (12)	34.6 ± 6.3	NS	NS	NS
Tsai et al. [221]	Smash	Elite (7)	62.5 ± NS	−7.43 ± NS	255 ± NS	NS
Tsai et al. [222]	Smash	Elite (1)	68	−11.5	NS	NS
Lee [232]	Smash	Sub-elite (NS)	54.26 ± NS	NS	NS	NS
Tsai et al. [221]	Smash	Collegiate (7)	54.2 ± NS	−7.02 ± NS	243 ± NS	NS
Tsai et al. [222]	Clear	Elite (1)	64	10.57 ± NS		
Hussain et al. [253]	Drop	Sub-elite (6)	61.92 ± 14.69	NS	NS	NS
Tsai et al. [222]	Drop	Elite (1)	29	−4.5	NS	NS
Hussain et al. [253]	Cut	Sub-elite (6)	18.66 ± 17.04	NS	NS	NS
Hussain et al. [224]	Forehand smash	Sub-elite (6)	67.00 ± 6.32	3.83 ± 0.75	2.39 ± 0.08	68.33 ± 5.21
	Backhand smash	Sub-elite (6)	52.67 ± 4.50	3.83 ± 0.41	2.24 ± 0.06	79.00 ± 5.10
Huang et al. [225]	Backhand smash	Junior (8)	52.1 ± 6.7	−4.0 ± 3.7	224.2 ± 7.8	81.0 ± 4.7
	Backhand clear	Junior (8)	53.0 ± 3.2	4.9 ± 4.2	231.7 ± 10.5	104.8 ± 4.6
	Backhand drop	Junior (8)	25.2 ± 4.2	22.1 ± 5.2	211.2 ± 12.3	90.8 ± 5.3
Hussain et al. [6]	Short serve	Sub-elite (6)	41.11 ± 25.03	46 ± 15.62	114 ± 0.05	NS
Hussain et al. [249]	Forehand short serve	Junior (8)	10.31 ± 3.47	NS	NS	11.80 ± 9.97
Hussain et al. [6]	Long serve	Sub-elite (6)	69.32 ± 17.71	51 ± 2.65	79 ± 0.04	NS
Hussain et al. [249]	Backhand short serve	Junior (8)	11.54 ± 5.20	NS	NS	96.00 ± 11.69
Females						
Tsai et al. [223]	Smash	Collegiate (7)	56.9 ± 3.74	−4.3 ± 2.23	NS	NS
	Clear	Collegiate (7)	57.8 ± 5.53	15.2 ± 2.84	NS	NS
	Drop	Collegiate (7)	59.6 ± 3.74	5.9 ± 4.56	NS	NS

Data are expressed as mean ± SD

NS not specified, *SD* standard deviation

[a] Shuttlecock coronal axis angular on sagittal plane

6.4 Summary

Elite players are able to launch the shuttlecock at high velocity due to the efficiency of a sequential proximo-distal joint action chain combined with the use of racket deflection. Moreover, badminton requires jumps, lunges, quick changes in direction and rapid arm movement from a wide variety of postural positions.

7 Conclusion

This review takes a global approach to badminton performance and to the interrelationship between various metabolic, physiological, biomechanical, technological and visual factors. Each of these factors may play an important role in the potential to optimize badminton performance. Future badminton research will likely continue to be heavily influenced by emerging racket technology and the evolution of physiological profiles. It is apparent that movement patterns and the physical demands of badminton are related to improving performance. Furthermore, it would be very interesting to compare badminton with other racket sports.

Studies reporting the physical characteristics of badminton have provided an understanding of players' anthropometric and physiological characteristics. Investigations of the physical characteristics of badminton players show a lean body composition and physiological requirement during a match. The design of aerobic and anaerobic training and test protocols will assist in training strategies. Knowledge of badminton improves coaching and badminton skills. Harnessing other disciplines will contribute new knowledge to the science of badminton.

Table 8 Kinematic values of badminton strokes

Study	Stroke	Subject (*n*)	Shoulder angle (°)	Elbow angle (°)	Wrist angle (°)	Shoulder angular velocity (°/s)	Elbow angular velocity (°/s)	Wrist angular velocity (°/s)
Males								
Tsai et al. [221]	Jump smash	Elite (7)	NS	NS	NS	−470 ± NS	1,035 ± NS	−1,447 ± NS
	Jump smash	Collegiate (4)	NS	NS	NS	−475 ± NS	538 ± NS	−996 ± NS
Rambely et al. [190]	Smash	Elite (12)	NS	NS	NS	−177.4 ± 285.5	171.4 ± 544.9	339.4 ± 818.3
Tsai et al. [221]	Smash	Elite (7)	NS	NS	NS	−479 ± NS	793 ± NS	−1,167 ± NS
Tsai et al. [222]	Smash	Elite (1)	164	194	166	−224	−784	−985
Tsai et al. [221]	Smash	Collegiate (4)	NS	NS	NS	−152 ± NS	569 ± NS	−984 ± NS
Tsai et al. [222]	Clear	Elite (1)	152	203	185	−266	−484	−1,427
Luhtanen et al. [226]	Clear	Junior (10)	119 ± NS[a]	118 ± NS[a]	168 ± NS[a]	1.4 ± NS[a]	14.0 ± NS[a]	0.3 ± NS[a]
Tsai et al. [222]	Drop	Elite (1)	145	202	196	−401	−174	−438
Hussain et al. [253]	Drop	Sub-elite (6)	46.50 ± 11.02	146.67 ± 4.63	213.67 ± 12.58	NS	NS	NS
	Cut	Sub-elite (6)	61.33 ± 31.85	142.50 ± 18.36	211.17 ± 9.00	NS	NS	NS
Hsueh et al. [169]	Dab	Sub-elite (8)	73.9 ± 50.1	NS	NS	NS	NS	7.3 ± 8.4
	Stab	Sub-elite (8)	70.7 ± 49.1	NS	NS	NS	NS	86.9 ± 22.9
	Cross-court	Sub-elite (8)	−107.5 ± 54.4	NS	NS	NS	NS	−89.4 ± 90.2
Hussain et al. [224]	Forehand smash	Sub-elite (6)	162.83 ± 11.69	188.33 ± 8.55	181.50 ± 9.35	605.50 ± 71.11	728.17 ± 8.77	1,718.50 ± 254.81
	Backhand smash	Sub-elite (6)	151.17 ± 5.04	185.67 ± 6.09	194.83 ± 4.45	229.33 ± 3.56	872.00 ± 46.85	1,393.70 ± 72.00
Huang et al. [225]	Backhand smash	Junior (8)	192.7 ± 20.7	169.5 ± 10.8	164.5 ± 11.2	−271.7 ± 122.6	745.7 ± 665.6	−1,497.4 ± 509.2
	Backhand clear	Junior (8)	176.5 ± 25.5	168.7 ± 10.1	178.3 ± 13.5	−184.1 ± 159.6	524.0 ± 488.8	−1,131.1 ± 569.0
	Backhand drop	Junior (8)	207.6 ± 57.6	150.1 ± 23.2	176.0 ± 32.8	−383.3 ± 270.8	862.0 ± 680.5	−591.7 ± 480.2
Hussain et al. [6]	Short serve	Sub-elite (6)	41 ± 17	133.67 ± 6.81	215 ± 9.17	NS	NS	NS
	Long serve	Sub-elite (6)	46.33 ± 9.29	148 ± 3.46	213 ± 17.69	NS	NS	NS
Smith et al. [196]	Long serve	Sub-elite (2)	NS	16.0 ± 0.02	59.7 ± 0.12	NS	NS	NS
	Long serve	Novice (1)	NS	34.2 ± 0.01	10.2 ± 0.06	NS	NS	NS
Hussain et al. [249]	Forehand short serve	Junior (8)	38.75 ± 8.77	130.75 ± 4.65	122.50 ± 8.74	NS	NS	NS
	Backhand short serve	Junior (8)	98.00 ± 31.60	132.75 ± 22.05	114.50 ± 17.86	NS	NS	NS
Females								
Tsai et al. [223]	Smash	Collegiate (7)	90.29 ± 20.98	205.5 ± 8.70	25.6 ± 9.00	−78 ± 206	176 ± 131	NS
	Clear	Collegiate (7)	79.92 ± 24.06	205.0 ± 6.15	33.0 ± 10.86	84 ± 136	203 ± 123	NS
	Drop	Collegiate (7)	72.01 ± 16.55	214.3 ± 3.58	43.5 ± 7.93	−125 ± 102	−110 ± 50	NS

Data are expressed as mean ± SD

NS not specified

[a] *rad/s* Radian per second

Based on this review, some practical advice can be given to coaches to improve badminton players' skills. An understanding of the temporal dynamics of the game could be used to design training schedules that reflect players' metabolic requirements, based on the known ratio of action time to rest time of approximately 1:2, and the high intensity and demands of rallies. The contribution of racket deflection to shuttlecock launch velocity suggests that a specific racket needs to be found for each player. Moreover, kinematic analysis reveals a specific coordination of events in the sequential proximo-distal joint action chain. This knowledge could help coaches focus on the specific action of each joint during the stroke, and design a training program that increases shuttlecock velocity.

Acknowledgments Michael Phomsoupha and Guillaume Laffaye have no potential conflicts of interest that are directly relevant to the content of this review. No sources of funding were used to assist in the preparation of this review.

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