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Activity profiles and physiological responses during match play in four popular racquet sports

A literature review

Introduction

Major racket sports are played by people of all levels, from competitive to recreational, in every part of the world (Fernandez-Fernandez, Sanz-Rivas, & Mendez-Villanueva, 2009). Four of the most popular of these major racquet sports are badminton, squash, table tennis, and tennis (Lees, 2003). Those can commonly be defined as sport activities in which two or four players use racquets to alternatively hit a shuttlecock or ball on a defined playing surface. The aim in each sport is to place the shuttlecock or ball in a certain position from which the opponent cannot successfully return it (Lees, 2003). Performance in those racquet sports is highly dependent on aerobic and anaerobic capacity and players require a mixture of fast reactions, anticipation, speed, agility, and flexibility to quickly reach a ball and thus prevent errors, but also require strength, technical ability, and tactical skills to return shots with high pace and accuracy to force an opponent to miss return (Fernandez, Mendez-Villanueva, & Pluim, 2006).

In order to enhance those skills by optimized training efficiency and competition preparation it is crucial to have comprehensive insight into the profile of requirements of the sports (Halson, 2014). This mainly depends on knowledge about activity profile and physiological responses during match play, what gets mainly affected by general match characteristics that are fundamentally determined by the respective rules of each sport.

In the last few decades, aiming to make rallies longer and thereby make the sports more attractive for the audience, there have been several adjustments to those fundamental rules in racquet sports, like new counting systems (Kondrič, Zagatto, & Sekulić, 2013; Phomsoupha & Laffaye, 2015) or ball sizes (Kondrič et al., 2013). Simultaneously, equipment-engineering technology has developed; in squash, for example, athletes are now able to create higher ball velocities using lighter racquets (Lees, 2003). This, together with a rise in the general fitness levels of competitive players, has lately led to striking changes in structure and intensity of racquet sports match play (Lees, 2003; Phomsoupha & Laffaye, 2015). Therefore, requests for up-to-date scientific research in match characteristics and training strategies of racquet sports have grown rapidly (Lees, 2003).

Thus, recently a lot of studies focusing on developments in activity profile and physiological responses of match play in badminton, squash table tennis or tennis have been published. However, to the best of our knowledge there is currently only one review summarizing and comparing parameters of the four major racquet sports (Lees, 2003). Therefore, the present narrative review aims to update the latest comparison by lately published results. This article should offer an overview about current rules and appropriate match characteristics in badminton, squash, table tennis and tennis. Moreover, an up-to-date profile of requirements, based on current developments of activity profile and physiological responses during match play in the four popular racquet sports, should be supplied.

Current rules and general match characteristics

Fundamentally, match play in badminton can be characterized by frequent changes of direction with high-acceleration movements following quick reactions (Manrique & Gonzalez-Badillo, 2003). In 2006, the Badminton World Federation (BWF) changed the scoring system from the traditional format (3 × 15) to a rally point scoring system (3 × 21), aiming to regulate playing time and make the sport more exciting for television viewers (Ming, Keong, & Ghosh, 2008). However, badminton is the only racquet sport played with a shuttlecock as an exceedingly kind of ball. Due to their atypical shape and lightness, shuttlecocks reach very high speeds and follow surprising flight trajectories. This requires the athletes to use all available visual information to anticipate the trajectory of the shuttlecock and the opponent's next displacement. To successfully return the shuttlecock the full length of the court, athletes need to perform various jumps and lunges, quick changes of direction, and rapid arm movements from a variety of postural positions (Phomsoupha & Laffaye, 2015). Players are therefore not only required to maintain high levels of concentration, but also of intensity. Since racquets and shuttlecocks in badminton are very light compared to squash and tennis, energy expenditure mainly depends on the athletes' morphological factors and displacement efficiency (Phomsoupha & Laffaye, 2015).

Against that, characteristics of squash match play mainly differ from the other three racquet sports as the opponents are not playing opposite, but rather next to each other and are not restricted to their courts or separated by a net (Wilkinson, Leedale-Brown, & Winter, 2009). At least in professional play, matches are conducted in a closed room of glass walls (Horobeanu & Rosca, 2014). This enables playing the ball through rebounds from the rear wall, which adds turning movements to the standard racquet sport movement patterns, like lunging or side-stepping (Wilkinson et al., 2009). Matches are played as the best-of-five sets, with, according to the current official scoring system, each set determined by the first player to reach 11 points with at least a two-point advantage (Lees & Maynard, 2004).

Like in squash, they also play best-of-five sets, with a scoring system up to 11 points in table tennis (Kondrič et al., 2013). Opponents meanwhile hit a 40-millimetre lightweight ball back and forth over a net on a table, using small bats (Malagoli Lanzoni, Di Michele, & Merni, 2014). Since table tennis is conducted on a small court, balls return with a very high-paced rhythm, characterising it as probably the fastest of the racquet sports. Thus, table tennis is a skill-dominated sport, and therefore the requirements for oxygen consumption during matches are comparatively low (Sperlich, Koehler, Holmberg, Zinner, & Mester, 2011). Match play is mainly characterized by its fast-paced rhythm and demand for quick reactions. Table tennis is often associated with high competitiveness, high intensity, and sophisticated techniques (Sperlich et al., 2011). Since courts in table tennis are restricted to a small table between the opponents, movements—especially in the lower limbs and shoulders—are characterized by a smaller range of motion, fewer jumps, and smaller distances than are observable in tennis, badminton, or squash. Although players also perform side steps and lunges to reach more distant balls, the strokes are predominantly performed by the upper body, compared to other racquet sports. This may require a lower amount of motor unit recruitment, leading to lower energy costs (Sperlich et al., 2011). Successful performance therefore seems to depend on athletes' technical and tactical skills (Malagoli Lanzoni et al., 2014) and muscular endurance, rather than cardiorespiratory capacity (Sperlich et al., 2011).

Tennis, in common with the other considered racquet sports, is also characterized by irregular, short, intermittent workloads of the body's entire muscular system (including trunk and upper extremity muscles), with mainly extensive and partly intensive work phases under high psychological stress (Fernandez-Fernandez, Kinner, & Ferrauti, 2010; Fernandez-Fernandez et al., 2009; Ferrauti, Bergeron, Pluim, & Weber, 2001a; Ferrauti, Pluim, & Weber, 2001c). Due to the higher weight of the racquets in tennis, even more than in other racquet sports, stroke production is a further important energetic demand factor, besides footwork and running activities (Fernandez-Fernandez et al., 2010). In addition, tennis is the only major sport that is officially played on different surfaces. Thus, tournaments can be conducted on carpeted, hard, clay, or grass surfaces, each requiring different abilities. In previous eras, athletes with powerful serves tended to dominate on fast surfaces (hard, grass), whereas strong baseliners often preferred slower courts (clay) (Fernandez et al., 2006). However, most modern elite players are all-rounders, playing excellently on all surfaces and introduction of specific balls in 2006 and changes to surface properties minimized the discrepancies (Fernandez-Fernandez et al., 2010; Fernandez-Fernandez et al., 2009).

Activity profile

Characteristics of activity profile contain temporal structure as well as notational aspects. Therefore, parameters like match duration, effective playing time, durations of rallies and recovery periods and work-to-rest ratios, often displayed as work density (active playing time divided by passive playing time), as well as number and frequency of strokes refer to the description of activity profile of racquet sports (Hoppe et al., 2019). Furthermore, total distances covered during match, as a measure of running activity, should be considered here. For measurement of those parameters several monitoring tools like video analysis, global or local positioning systems (GPS/LPS) or accelerometers have recently been implemented in sports investigations (Halson, 2014). Results of the sighted studies according to activity profile and running activities of the four racquet sports are presented in **Table 1**.

Research showed, that in badminton matches last between 17–40 min (Abian-Vicen et al., 2013; Ming et al., 2008), but most take approximately 30 min (Faude et al., 2007). Several studies reporting on badminton match structures have characterized the game as highly intermittent and consisting of short rally intervals (mean of 7.5 s) interrupted by in relation long resting intervals (mean of 18.6 s). Effective playing time therefore accounts for an average of 30.1% of the total match duration (Abian-Vicen et al., 2013; Abián et al., 2014; Cabello et al., 2004; Chen & Chen, 2008; Chen & Chen, 2011; Faude et al., 2007; Manrique & Gonzalez-Badillo, 2003; Ming et al., 2008), while work densities from a low of 0.36 to a high of 0.57 have been calculated (Abian-Vicen et al., 2013; Abián et al., 2014). In addition, notational analyses of badminton match play have pointed to a high striking frequency, with mean values from 0.92–1.09 strokes per second (Abian-Vicen et al., 2013; Abián et al., 2014; Manrique & Gonzalez-Badillo, 2003), with 4.4–5.1 strokes per rally (Alcock & Cable, 2009; Faude et al., 2007). During a match, athletes cover distances of 1763 ± 751 m (Abdullahi et al., 2019).

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Activity profiles and physiological responses during match play in four popular racquet sports. A literature review

Abstract

Badminton, squash, table tennis, and tennis are four of the most popular racquet sports. In recent years, modifications in rules, equipment, and athletes' physical fitness have led to changes in match structure and therefore also in demands on athletes of these sports. This has caused a sudden rise in requests for scientific research, since insight into a sport's profile of requirements is crucial for efficient training monitoring. This review aims to offer a comprehensive overview about latest findings about activity profile and physiological responses in match play in the four racquet sports. Comparisons showed that the match structure of each of the four racquet sports is similar with regard to the intermittent character, but differences appear across all disciplines when comparing match, rally, and resting interval durations, work density, covered distances, and striking frequencies. Moreover, high average cardiorespiratory responses are reported for badminton and squash, but not for table tennis and tennis. In all racquet sports, continuous changes in high-intensity movement and periods of recovery are found, suggesting significant influence of both aerobic and anaerobic alactic energetic pathways. In contrast, lactic pathways seem to play an important role in squash, but less in the other racquet sports. These discrepancies in energetic demands are related to the differences in the total amounts of effort and recovery and their relationship to each other. To conclude, the four racquet sports have a lot in common, but each sport brings its own requirements. Badminton is highly dependent on reaction and anticipation, squash is high-intensity, table tennis is mostly skill-related, and tennis is less intensive, but of greatest volume of effort.

Keywords

Badminton · Squash · Table tennis · Tennis · Match play characteristics

Belastungs- und Beanspruchungsprofil von vier populären Rückschlagsportarten während eines Spiels. Ein Literaturreview

Zusammenfassung

Badminton, Squash, Tischtennis und Tennis zählen zu den beliebtesten Rückschlagsportarten. Änderungen innerhalb der Spielregeln, bezüglich der Ausrüstung und der allgemeinen physischen Leistungsfähigkeit der Athleten, haben bewirkt, dass sich die Spielstruktur und damit auch die Anforderungen an die Spieler verändert haben. Da es für eine möglichst effiziente Trainingssteuerung notwendig ist, das Anforderungsprofil des Sports genau zu kennen, hat dies zu einem rapiden Anstieg der Nachfrage nach evidenzbasiertem Wissen zu Rückschlagspielen geführt. Dieses Review soll einen umfangreichen Überblick über das Belastungs- und Beanspruchungsprofil in Badminton, Squash, Tischtennis und Tennis geben. Ein Vergleich zeigt, dass sich die Matchstruktur der vier Sportarten hinsichtlich der intervallartigen Gestaltung ähnelt, sich diese Intervalle allerdings nach Sportarten unterscheiden lassen. So konnten hinsichtlich der durchschnittlichen Spieldauer, Ballwechsel- und Pausenzeiten, Arbeitsdichte, Schlagfrequenz und der zurückgelegten Distanzen sportartspezifische und charakteristische Unterschiede festgestellt werden. Hinsichtlich der physiologischen Beanspruchung konnten die höchsten durchschnittlichen kardiorespiratorischen Werte im Squash und Badminton gezeigt werden, während diese in Tischtennis und Tennis deutlich geringer ausfallen. Der kontinuierliche Wechsel zwischen hochintensiven Spielphasen und kurzen Phasen der Regeneration ist charakteristisch für alle vier betrachteten Sportarten, weshalb von einer hohen Beteiligung der anaerob alaktaziden, aber auch der aeroben Stoffwechselvorgänge an der Energiebereitstellung ausgegangen werden kann. Die anaerob laktazide Kapazität scheint hingegen ausschließlich in Squash ein leistungslimitierender Faktor zu sein. Diese Charakteristika sind wiederum auf die unterschiedliche Intervallgestaltung der jeweiligen Matchstruktur zurückzuführen. Zusammengefasst kann festgehalten werden, dass die Belastungs- und Beanspruchungsformen der vier Sportarten durchaus einiges gemeinsam haben und dennoch jede Disziplin ihre eigenen Anforderungen mit sich bringt.

Schlüsselwörter

Badminton · Squash · Tischtennis · Tennis · Spielcharakteristika

Single sets in squash usually last about 16 min. Since matches can consist of three to five sets, match durations mostly take between 48 and 81 min (Girard et al., 2007; Montpetit, 1990; Vučkovic et al., 2005; Vučkovic & James, 2010). Vučkovic et al. (2005) reported the shortest sets to be of 5 min, up to the longest of 32 min for the World Team Championships (Vienna) and Slovene National Championships (Ljubljana) in 2003. Squash match play is characterized by long rallies (mean of 17.5 s) interrupted by relatively short resting periods (mean of 9 s). Therefore, although the total playing time might be quite short, the proportion of effective playing time (average of 59.2%) is very high (Girard et al., 2007; Hughes & Robertson, 2002; Montpetit, 1990; Vučkovic et al., 2005; Vučkovic & James, 2010). Girard et al. (2007), who examined match characteristics of elite squash players, reported a mean effective playing time as high as 69.7%. They further calculated a corresponding work density of 2.4, demonstrating that squash match play is very intense, as there is both high effort and little time to recover. International players cover distances of approximately 1119 m per game what, depending upon the number of sets, comply with total distances of about 3300–5600 m (Vučkovic

Table 1 External loads during match play in the four racquet sports (mean values expressed as mean ± standard deviation)

Parameter	Sport	Study	Specification	Values
Match duration [min]	Badminton	Abian-Vicen, Castanedo, Abian, & Sampedro (2013)	–	39.6 ± 6.5
		Abián, Castanedo, Feng, Sampedro, & Abian-Vicen (2014)	–	18.7 ± 3.8
		Cabello, Padial, Lees, & Rivas (2004)	–	34.8 ± 15.4
		Chen & Chen (2008)	–	32.5 ± 2.5
		Manrique & Gonzalez-Badillo (2003)	–	28.7 ± 5.2
		Ming et al. (2008)	–	17.3 ± 2.7
	Squash	Girard, Chevalier, Habrard, & Sciberras (2007)	–	25.1 ± 4.0
		Montpetit (1990)	–	11.6 ± n. s.
		Vučkovic, Dezman, Pers, & Kovacic (2005)	IN:	16.8 ± 6.7
			N:	9.9 ± 4.7
		Vučkovic & James (2010)	–	16.8 ± 6.7
	Table Tennis	Katsikadelis, Pilianidis, & Vasilogambrou (2007)	–	22.8 ± 5.8
		Zagatto, Morel, & Gobatto (2010)	–	16.2 ± 5.6
	Tennis	Hornery, Farrow, Mujika, & Young (2007)	Clay:	79.0 ± 13.0
			Hard:	119.0 ± 36.0
		Mendez-Villanueva, Fernandez-Fernandez, Bishop, Fernandez-Garcia, & Terrados (2007)	–	105.0 ± 35.7
Rally duration [s]	Badminton	Abian-Vicen et al. (2013)	Set 1:	9.0 ± 0.9
			Set 2:	9.1 ± 1.4
		Abián et al. (2014)	Set 1:	09.0 ± 1.1
			Set 2:	10.4 ± 2.1
		Cabello et al. (2004)	–	7.3 ± 1.3
		Chen & Chen (2008)	–	8.2 ± 0.2
		Chen & Chen (2011)	–	6.0 ± 0.6
		Faude et al. (2007)	–	5.5 ± 4.0
		Manrique & Gonzalez-Badillo (2003)	–	6.4 ± 1.3
		Ming et al. (2008)	–	4.6 ± 0.9
	Squash	Girard et al. (2007)	–	18.6 ± 4.6
		Hughes & Robertson (2002)	–	21.0 ± n. s.
		Montpetit (1990)	–	13.6 ± n. s.
		Vučkovic & James (2010)	–	16.6 ± 16.2
	Table Tennis	Zagatto et al. (2010)	–	3.4 ± 1.7
	Tennis	Fernandez-Fernandez, Fernandez-Garcia, Mendez-Villanueva, & Terrados (2005)	–	7.5 ± 7.3
		Hornery et al. (2007)	Clay:	7.5 ± 3.0
			Hard:	6.7 ± 2.2
		Mendez-Villanueva et al. (2007)	–	7.5 ± 7.3
		Murias, Lanatta, Arcuri, & Laino (2007)	Clay:	8.8 ± 5.3
			Hard:	7.2 ± 4.4
		Smekal et al. (2001)	–	6.4 ± 4.1

et al., 2005; Vučkovic & James, 2010) and perform 0.3 strokes per second (4.8 strokes per rally) (Montpetit, 1990).

Despite the popularity of table tennis, only a little is known about activity profile of match play, so far (Kondrič et al., 2013). One study by Zagatto et al. (2010) estimated the temporal structure of regional and international table tennis match play. According to their investigations, matches lasted an average of 16 ± 5 min, of which 44.3% was considered to be effective playing time. Katsikadelis et al. (2007) reported slightly higher values of an average of 23 ± 6 min per match, with the shortest matches of 9 min and the longest of 38 min. The significant differences in match duration may be due to the number of sets (three or five) that have to be played to decide the winner. As the match structure is very frequent, and match durations are comparatively short, both rally and rest intervals are quite brief (3.4 ± 1.7 s

Table 1 (Continued)

Parameter	Sport	Study	Specification	Values
Rest duration [s]	Badminton	Abian-Vicen et al. (2013)	Set 1:	24.1 ± 3.8
			Set 2:	25.2 ± 4.6
		Abián et al. (2014)	Set 1:	24.7 ± 4.3
			Set 2:	26.7 ± 4.6
		Cabello et al. (2004)	–	14.2 ± 3.4
		Faude et al. (2007)	–	11.4 ± 6.0
		Manrique & Gonzalez-Badillo (2003)	–	12.9 ± 2.7
		Ming et al. (2008)	–	9.7 ± 1.3
	Squash	Girard et al. (2007)	–	8.0 ± 1.8
		Hughes & Robertson (2002)	–	10.0 ± n. s.
		Montpetit (1990)	–	9.0 ± n. s.
	Table Tennis	Zagatto et al. (2010)	–	8.1 ± 5.1
	Tennis	Fernandez-Fernandez et al. (2005)	–	16.2 ± 5.2
		Hornery et al. (2007)	Clay:	17.2 ± 3.3
			Hard:	25.1 ± 4.3
		Mendez-Villanueva et al. (2007)	–	16.2 ± 5.2
		Murias et al. (2007)	Clay:	19.4 ± 8.6
			Hard:	20.2 ± 7.7
Effective playing time [%]	Badminton	Abian-Vicen et al. (2013)	Set 1:	28.1 ± 3.4
			Set 2:	27.3 ± 2.4
		Abián et al. (2014)	Set 1:	27.7 ± 2.9
			Set 2:	28.0 ± 2.7
		Chen & Chen (2011)	–	36.4 ± 2.4
		Faude et al. (2007)	–	31.2 ± 2.8
		Ming et al. (2008)	–	32.2 ± 3.3
	Squash	Girard et al. (2007)	–	69.7 ± 4.7
		Montpetit (1990)	–	60.1 ± n. s.
		Vučkovic & James (2010)	–	55.0 ± n. s.
				54.4 ± n. s.
		Vučkovic et al. (2005)	–	56.6 ± n. s.
	Table Tennis	Zagatto et al. (2010)	–	44.3 ± 23.7
	Tennis	Fernandez-Fernandez et al. (2005)	–	18.2 ± 5.2
		Mendez-Villanueva et al. (2007)	–	21.5 ± 4.9
		Smekal et al. (2001)	–	29.3 ± 12.1

and 8.1 ± 5.1 s, respectively). Work density (0.4) could be considered moderate, with a mean of 4.5 strokes per rally (Zagatto et al., 2010).

Against that, match play in tennis often lasts between 1–5 h (Fernandez-Fernandez et al., 2009; Fernandez et al., 2006; Kovacs, 2007). Resting intervals thereby on average take 19.1 s, which is quite long compared to the short average rally durations of 7.4 s. Work density is about 0.5, while stroke frequencies are up to 0.7 strokes per second, accounting for an average of 3.7 strokes per rally, which is quite low compared to other racquet sports (Fernandez-Fernandez et al., 2005; Hornery et al., 2007; Mendez-Villanueva et al., 2007; Murias et al., 2007; Smekal et al., 2001). Nevertheless, Fernandez-Fernandez et al. (2010) demonstrated that oxygen consumption increases up to 85% of VO_2 max during 40 maximal forehand or backhand strokes (from a standing position with stroke frequency of 2 s), indicating that strokes do play an important role with respect to performance limitations. In addition, almost 80% of strokes during match play take place within 2.5 m of the player's ready position, about 10% occur in a range of 2.5–4.5 m—mostly achieved by a sliding type of movement—and less than 5% of strokes require more than 4.5 m of movement, forcing players into a running-type movement pattern. Thus, overall athletes cover distances of up to 3600 m per hour of play (Fernandez-Fernandez et al., 2009).

To sum up, comparing the activity profiles of the four racquet sports showed that match activity can commonly be characterized by high-frequency changes from

Table 1 (Continued)

Parameter	Sport	Study	Specification	Values
Work density	Badminton	Abian-Vicen et al. (2013)	Set 1:	0.4 ± 0.1
			Set 2:	0.4 ± 0.0
		Abián et al. (2014)	Set 1:	0.4 ± 0.1
			Set 2:	0.4 ± 0.0
		Cabello et al. (2004)	–	0.5 ± 0.1
		Chen & Chen (2011)	–	0.6 ± 0.1
		Faude et al. (2007)	–	0.5 ± 0.3
		Manrique & Gonzalez-Badillo (2003)	–	0.5 ± 0.1
		Ming et al. (2008)	–	0.5 ± 0.1
	Squash	Girard et al. (2007)	–	2.4 ± 0.6
	Table Tennis	Zagatto et al. (2010)	–	0.4 ± 0.2
	Tennis	Fernandez-Fernandez et al. (2005)	–	0.5 ± n. s.
		Mendez-Villanueva et al. (2007)	–	0.5 ± 0.3
		Murias et al. (2007)	Clay:	0.5 ± n. s.
			Hard:	0.3 ± n. s.
	Badminton	Abian-Vicen et al. (2013)	Set 1:	1.08 ± 0.04
			Set 2:	1.09 ± 0.03
Striking frequency [s^{-1}] (Shots per rally) [rally^{-1}]	Badminton	Abián et al. (2014)	Set 1:	1.09 ± 0.03
			Set 2:	1.07 ± 0.04
		Alcock & Cable (2009)	–	4.4 ± 0.3
		Chen & Chen (2008)	–	1.05 ± 0.02
		Chen & Chen (2011)	–	1.03 ± 0.07
		Faude et al. (2007)	–	0.92 ± 0.31
				5.1 ± 3.9
		Manrique & Gonzalez-Badillo (2003)	–	0.93 ± 0.11
		Ming et al. (2008)	–	1.03 ± 0.22
	Squash	Montpetit (1990)	–	0.30 ± n. s.
				4.8 ± n. s.
	Table Tennis	Malagoli Lanzoni et al. (2014)	–	5.11 ± n. s.
		Zagatto et al. (2010)	–	0.59 ± 0.13
				3.9 ± 2.0
	Tennis	Fernandez-Fernandez et al. (2005)	–	2.80 ± 2.10
		Hornery et al. (2007)	Clay:	4.5 ± 2.0
			Hard:	4.7 ± 1.4
		Mendez-Villanueva et al. (2007)	–	2.7 ± 2.2
		Smekal et al. (2001)	–	0.7 ± 0.20
Covered distance [m]	Badminton	Abdullahi, Coetzee, & Berg (2019)	–	1763 ± 751
	Squash	Vučkovic et al. (2005)	IN:	1118 ± 425
			N:	617 ± 307
		Vučkovic & James (2010)	–	1119 ± 426
	Tennis	Fernandez-Fernandez et al. (2009)	–	3568 ± 532

IN values measured in match play of international players, *N* values measured in match play of national players, ***n. s.*** not specified

moderate to very intense whole-body activities, which are interrupted by periods of active or passive recovery (Faude et al., 2007; Fernandez et al., 2006; Girard et al., 2007; Sperlich et al., 2011). However, comparison of the reported data also suggests some differences in temporal structure and the notational habits of each sport.

The longest matches were reported in tennis. Match duration in badminton is far below these values, but still almost twice as long as matches in table tennis. Match duration in squash is highly dependent on the number of played sets and the level of the players, but usually lies somewhere between badminton and tennis. Furthermore, the sports differ in

Table 2 Internal loads during match play in the four racquet sports (mean values expressed as mean ± standard deviation)

Parameter	Sport	Study	Values
HR [bpm]	Badminton	Faude et al. (2007)	166 ± 6
		Chen & Chen (2011)	179 ± 2
		Manrique & Gonzalez-Badillo (2003)	173 ± 9
	Squash	Girard et al. (2007)	177 ± 10
		Montpetit (1990)	160 ± n. s.
	Table Tennis	Zagatto et al. (2010)	164 ± 14
		Sperlich et al. (2011)	125 ± 22
	Tennis	Ferrauti et al. (2001a)	143 ± 13
		Smekal et al. (2001)	151 ± 18
VO_2 [$ml \cdot kg^{-1} \cdot min^{-1}$]	Badminton	Faude et al. (2007)	46.0 ± 4.5
		Liddle, Murphy, & Bleakley (1996)	54.5 ± 2.5
		Majumdar et al. (1997)	55.7 ± 4.4
	Squash	Girard et al. (2007)	54.4 ± 4.8
	Table Tennis	Sperlich et al. (2011)	25.6 ± 10.1
	Tennis	Fernandez-Fernandez et al. (2005)	26.6 ± 3.3
		Ferrauti, Schulz, Strüder, Heck, & Weber (1998)	24.2 ± 2.0
		Ferrauti et al. (2001a)	25.6 ± 2.8
		Smekal et al. (2001)	29.1 ± 5.6
LA [$mmol \cdot l^{-1}$]	Badminton	Cabello et al. (2004)	3.8 ± 0.9
		Chen & Chen (2011)	4.6 ± 0.4
		Faude et al. (2007)	1.9 ± 0.1
		Majumdar et al. (1997)	4.7 ± 1.9
	Squash	Girard et al. (2007)	8.3 ± 3.4
	Table Tennis	Zagatto et al. (2010)	1.8 ± 0.7
		Sperlich et al. (2011)	1.1 ± 0.2
	Tennis	Fernandez-Fernandez et al. (2005)	3.8 ± 2.0
		Ferrauti et al. (1998)	1.5 ± 0.7
		Ferrauti et al. (2001a)	1.7 ± 0.5
		Mendez-Villanueva et al. (2007)	3.8 ± 2.0
		Smekal et al. (2001)	2.1 ± 0.9

HR mean heart rate, *VO_2* mean oxygen uptake, *LA* mean blood lactate values, ***n. s.*** not specified

total length of rally and resting intervals and in their relationship to each other. Average rally duration in tennis and badminton are twice as long as rally durations observable in table tennis, while rally intervals in squash exceed the other three by almost three times. The longest resting intervals between rallies were reported for tennis and badminton, respectively while resting intervals in squash and table tennis are comparatively short. Due to quite short resting periods in relation to long corresponding rally durations, effective playing time in squash, clearly exceeds the values observed in tennis, while effective playing times in badminton and table tennis lie in between. Consequently, work densities in badminton, table tennis, and tennis are approximately five times lower than in squash.

Against this, the highest volumes of effort could be observed in tennis. With respect to match duration and due to the larger playing courts, tennis players are required to run strikingly longer distances during competition than they commonly do in badminton and slightly longer than in squash. Covered distances in table tennis have not been reported so far, but as activity of the lower limbs in table tennis is characterized by highly reactive movements that are conducted nearly on-the-spot (Sperlich et al., 2011), displacement is probably negligible in the player profile and would be expected to be far below the values observed in the other sports. However, displacement is not the only demanding factor in racquet sports, as striking patterns are also significant (Fernandez-Fernandez et al., 2010). The various strokes in the different racquet sports not only differ in technical and biomechanical aspects, but also in striking frequency. The highest average frequencies have been reported in badminton. They are much higher than the striking frequencies in tennis and table tennis and almost three times as fast as reported for squash. These results are somewhat surprising. Since the number of strokes per rally in table tennis is similar to those observed in squash or badminton, and even higher than reported for tennis, but, simultaneously, rally times are shorter, stroke frequency would be expected to be much higher. This inconsistency could be explained by methodical deviations, as it is unclear whether the article authors included resting intervals in calculating stroke frequency. Therefore, care has to be taken when comparing striking patterns between the sports.

Physiological responses

Typically reported parameters with respect to physiological responses refer to physiological and psychological stress (e.g., mean and maximum heart rate [HR], percentage of time spent in different heart rate zones, blood lactate concentrations [LA], oxygen consumption [VO_2], metabolic output, substrate oxidation, and different psychometric indications of exhaustion and psychophysiological stress) (Halson, 2014; Hoppe et al., 2019). Those internal parameters are usually assessed via heart rate monitoring, results from portable gas exchange measurement devices, or analysis of blood samples. Additionally, measurements of catecholamine concentrations (an indicator of sympathetic activation) (Ferrauti et al., 2001c), allow for quantification of psychophysiological stress and fatigue (Halson, 2014). Results referring to the physiological responses are summarized in **Table 2**.

In badminton, studies on match play have commonly demonstrated quite high cardiorespiratory responses. Mean HR values of 166 to 179 bpm have been reported during simulated (Chen & Chen, 2011; Faude et al., 2007) and 173 bpm, up to peak values of 190 bpm, during competitive match play (Manrique & Gonzalez-Badillo, 2003). Only a few studies have measured oxygen consumption during badminton match play, finding mean VO_2 values of 46.0, 54.5, and 55.7 $ml \cdot kg^{-1} \cdot min^{-1}$ (Faude et al., 2007; Liddle et al., 1996; Majumdar et al., 1997). According to those findings (Faude et al., 2007), badminton match play was suggested to predominantly demand on aerobic and anaerobic alactic—rather than lactic—energy pathways. This assumption seems to be confirmed, since the reported mean values of blood lactate concentrations, which range from 1.9 $mmol \cdot l^{-1}$ under simulated conditions (Faude et al., 2007) to 4.7 $mmol \cdot l^{-1}$ under real match conditions (Majumdar et al., 1997), are comparatively low.

In squash, in line with the high work density (Girard et al., 2007), very high values for average HR (177 ± 10 bpm) and VO_2 (54.4 ± 4.8 $ml \cdot kg^{-1} \cdot min^{-1}$, corresponding to 86% VO_2 max) have been observed. That becomes even more significant when considering that those values are sustained throughout the entire match. As expected, due to the frequent periods of high intensity, measured blood lactate concentrations (up to 8 $mmol \cdot l^{-1}$) indicate that there is also high demand on the anaerobic lactic energy system (Girard et al., 2007).

Against that, reported values in table tennis of HR (125 ± 22 bpm), VO_2 (25.6 ± 10.1 $ml \cdot kg^{-1} \cdot min^{-1}$), and blood lactate concentration (1.1 ± 0.2 $mmol \cdot l^{-1}$) are fairly low, suggesting comparatively low intensities during match play (Sperlich et al., 2011; Zagatto et al., 2010). With respect to the estimated lactate concentrations, energy might be predominantly derived from aerobic and anaerobic alactic pathways (Sperlich et al., 2011; Zagatto et al., 2010). The aerobic system, is mainly responsible for recovery during resting intervals and creates ideal physical conditions for the next rally (Zagatto et al., 2010), while the anaerobic alactic metabolism becomes important during the short high-intensity playing periods (Kondrič et al., 2013). Sperlich et al. (2011) suggested that, based on low cardiorespiratory responses, especially of the mean respiratory quotient, lipid oxidation seems to play a greater role in table tennis than it does in other racquet sports.

Similarly, also in tennis markedly smaller cardiorespiratory responses (mean HR 147 bpm and mean VO_2 21.1 $ml \cdot kg^{-1} \cdot min^{-1}$) compared to squash or badminton have been reported. This may be explained by the comparatively long resting periods during a match, which offer athletes a lot of time to recover between rallies. Aerobic submaximal activities therefore tend to exceed the short high-intensity intervals (Fernandez-Fernandez et al., 2009). In addition, average blood lactate concentrations (commonly about 1.8–3.8 $mmol \cdot l^{-1}$) are usually comparatively low (Fernandez-Fernandez et al., 2005; Ferrauti et al., 1998; Ferrauti et al., 2001a; Mendez-Villanueva et al., 2007; Smekal et al., 2001).

In addition, with respect to psychophysiological stress during match play, Ferrauti, Neumann, Weber, & Keul (2001b) found that postcompetition urine concentrations of adrenaline and noradrenaline in tennis players increased significantly under real tournament conditions compared to match play under training conditions. This data highlights that athletes, beyond physiological loads, must also sustain very high psychological stress during match play (Ferrauti et al., 2001c). As similar results have been reported for table tennis (Baron et al., 1992), the most likely explanation is the specific rules and demands common to racquet sports (e.g., no draws, no teammates, no time limits, high coordinative demands) (Ferrauti et al., 2001b), suggesting that this finding may be true of all four of the considered racquet sports.

To summarize, in line with the intermittent character of activity profile, physiological responses in racquet sports are also characterized by continuous fluctuations displayed in cardiorespiratory and metabolic demands (Reid, Duffield, Dawson, Baker, & Crespo, 2008). Commonly, appropriate values rise rapidly at the beginning of a match, remain constantly high (up to mean HR of 92% of maximum HR reported during squash match play (Girard et al., 2007)) during the remaining match time and partly recover during longer breaks—either at changeovers or between the sets.

Typically, cardiorespiratory demands in tennis and table tennis are markedly below those, observable in badminton and squash. This could be explained, as in table tennis, most movements are conducted within a smaller range of motion than other racquet sports, and rallies are quite short. That may lead to less energetic requirements and therefore lower cardiorespiratory answer than observable in other racquet sports. In tennis the overall lower respiratory responses could rather be explained by the shortness of rallies (>80% of all points involve fewer than four strokes per player). The rest periods between the rallies and during changes of ends are therefore usually long enough for the regeneration of PCr and ATP stores (Ferrauti, 2019).

Nevertheless, even though VO_2 consumption, and therefore relative energy expenditure (41.8 $kJ \cdot min^{-1}$), in tennis is somewhat lower than in badminton (53.3 $kJ \cdot min^{-1}$) or squash (82.2 $kJ \cdot min^{-1}$), total aerobic energy supply is still similar or even higher (e.g., 2544 kJ for a short match of one hour of tennis and 2328 kJ for a long badminton match of half an hour, calculated for 80 kg men), due to longer match durations, greater distances, and a greater number of very demanding strokes (Faude et al., 2007; Ferrauti et al., 2001a; Girard et al., 2007). In addition, it has been suggested that performance during match play in racquet sports is dependent on aerobic and anaerobic alactic capacities rather than lactic capacity. The anaerobic alactic system delivers energy during short, high-intensity rally intervals, and aerobic metabolism is responsible for recovery of ATP-PCr stores during resting intervals in between. But, length of rallies, resting intervals, and the relationship between them do strongly determine the influence of the different energy delivery systems. As higher work density, higher

Table 3 Overview of included articles

Sport	Study	Description
Tennis	Fernandez-Fernandez et al. (2005)	International (8)/R
	Ferrauti et al. (2001b)	National (12)/S
	Ferrauti et al. (1998)	National (12)/S
	Hornery et al. (2007)	International (14)/R
	Mendez-Villanueva et al. (2007)	International (8)/R
	Murias et al. (2007)	National (4)/S
	Smekal et al. (2001)	National (20)/S
Badminton	Abdullahi et al. (2019)	International (12)/R
	Abian-Vicen et al. (2013)	Olympic (20)/R
	Abián et al. (2014)	Olympic (40)/R
	Cabello et al. (2004)	National (79)/R
	Chen & Chen (2008)	International (16)/S
	Faude et al. (2007)	International (12)/S
	Liddle et al. (1996)	Elite (10)/
	Majumdar et al. (1997)	National (6)/S
	Manrique & Gonzalez-Badillo (2003)	International (11)/R
	Ming et al. (2008)	National (16)/R/Y
Squash	Girard et al. (2007)	National (7)/S
	Hughes & Robertson (2002)	International/R
	Vučkovic et al. (2005)	International (16)/R National (14)/R
	Vučkovic & James (2010)	International (16)/R
Table Tennis	Katsikadelis et al. (2007)	International (60)/R
	Sperlich et al. (2011)	International (7)/R/Y
	Zagatto et al. (2010)	Regional-International (20)/R

n number of subjects, *R* measurements during real competitive match, *S* measurement during simulated or training match play, *Y* young players

values of effective playing time, and shorter resting intervals, lead to a higher amount of blood lactate accumulation with simultaneously less time for lactate elimination, it is not surprising that lactic amount in badminton, table tennis and tennis is much lower than in squash (Girard et al., 2007).

Limitations and perspectives for future research in racquet sports

With respect to interpretation of these results, there are some limitations to the present research that should be considered. First, the research showed that evidence is still quite unequally spread across the different sports. A lot is known about activity profile and physiological responses in tennis and badminton, but less in squash and table tennis. In addition, except for tennis, very little data has been reported so far on the kinematic characteristics of racquet sports. Second, since measurement devices disturb players' movements, most studies, especially those reporting cardiorespiratory values, are still based on data generated during training match play (simulated matches). This may be a huge problem, since psychophysiological stress seems to be greater in real matches than in training match play (Baron et al., 1992; Ferrauti et al., 2001b), and external and internal loads might therefore be consistently underestimated in the existing literature.

A possible solution for both problems could be offered by innovative measurement approaches, like accelerometers, GPSs, or LPSs. These technologies allow for calculation of internal loads (like metabolic power and energy expenditure) from recordings of external loads and would supply additional information about displacement, velocity, and acceleration of an athlete during a game (Hoppe et al., 2014; Hoppe, Baumgart, & Freiwald, 2018a). Athletes need wear only a small transmitter, which is minimally disruptive and may therefore be worn during real tournaments. Such techniques are already established in other sports, but so far not in racquet sports. Nevertheless Hoppe, Baumgart, Polglaze, & Freiwald (2018b) recently validated an LPS approach for racquet sports and even conducted the first studies with respect to movement patterns in tennis (Hoppe et al., 2014). Further investigations should also consider implementing the LPS technique in racquet sports measurements.

Another aspect that is still largely ignored is the lack training strategy knowledge. Recent investigations with elite male tournament players in tennis revealed that intensity, density, and duration of training stimuli often exceeds the physiological demands of match play (Ferrauti et al., 2001b). Similar results have been reported in badminton, with Ghosh (2008) finding far higher lactate concentrations during training than those observed in match play. In this regard, future research should seriously consider evaluation of internal loads and coordinative effects of common on-court drills in all racquet sports.

Additionally, due to the special features of the movement patterns and metabolic demands in racquet sports, endurance testing of racquet sport players should also mimic the specific coordinative, physiological, and neuromuscular demands of match play as accurately as possible to increase the validity of the testing results (Ferrauti, Kinner, & Fernandez-Fernandez, 2011; Girard, Chevalier, Leveque, Micallef, & Millet, 2006). Future research should therefore consider the construction of specific endurance testing for racquet sports (Fernandez-Fernandez, Ulbricht, & Ferrauti, 2014; Ferrauti, Ulbricht, & Fernandez-Fernandez, 2018).

A major limitation of the review that also has to be noted is that this review did not differ between data estimated in youth or adult players or results basing on simulated or real matches. In addition, though studies referring to recreational

Table 4 Comparative overview of activity profile and physiological responses during match play in the four racquet sports (assessments in comparison of the sport with the other three considered racquet sports)

		BM	SQ	TT	TE
Activity profile	Match duration	↔	↔	↓	↑
	Rally length	↔	↑	↓	↔
	Resting length	↔	↓	↓	↑
	Effective playing time	↔	↑	↔	↓
	Work density	↔	↑	↔	↓
	Covered distances	↔	↑	↓	↑
	Stroke frequency	↑	↓	↑	↔
Physiological responses	Cardiorespiratory demands (HR, VO_2)	↑	↑	↓	↓
	Total energy consumption	↑	↑	↓	↑
	Lipid-oxidation	↓	↓	↑	↓
	Aerobic Carboxylation	↑	↑	↔	↑
	Anaerobic Carboxylation	↔	↑	↓	↓

BM Badminton, *SQ* Squash, *TT* Table tennis, *TE* Tennis, *HR* mean heart rate, VO_2 mean oxygen uptake, ↑ high, ↔ moderate, ↓ low

players have been excluded, still striking differences in playing level of the participants of the single studies can be expected. To clarify that, **Table 3** gives an overview about included studies and their appropriate study design, referring to the differing aspects. Furthermore, this review only refers to data estimated in men's singles matches, what might be a further limitation as, although differences in activity profiles of male and female players, at least in tennis, are getting smaller (Fernandez-Fernandez et al., 2009), there are still discrepancies in physiology, morphology, and style of play between the genders in tennis, badminton, and table tennis (Faude et al., 2007; Fernandez-Fernandez et al., 2009; Katsikadelis et al., 2007). Even greater discrepancies occur when singles are compared to doubles match play (Alcock & Cable, 2009). Care should therefore be taken, as the results of men's singles cannot be simply transferred to women's or doubles match play. Lastly, there should be mentioned that data of physiological responses in this review is based on absolute values, comparisons should therefore be regarded with caution.

Conclusion

To summarize, previous studies have noted that racquet sports can commonly be characterized by high-frequency changes from moderate to very intense whole-body activities, which are interrupted by periods of active or passive recovery, but may differ in general aspects of match characteristics, their activity profile and therefore also in physiological responses (Fernandez et al., 2006). In line with this, racquet sports also differ in the amount of utilization of metabolic pathways for energy delivery during matches (Reid et al., 2008). What they have in common is that all athletes require both high aerobic and anaerobic alactic capacity, but lactic capacity has a greater influence on performance only in the case of squash. **Table 4** gives a short, comparative overview about the specific aspects of each discipline. Moreover, although scientific research has rapidly increased during the last few decades, there is still a need for further research, which should consider the implementation of new technologies to enhance data quality, reflect estimations of training drills to enhance understanding and monitoring of training, and examine the construction of specific testing strategies to gather more conclusive data.

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Compliance with ethical guidelines

Conflict of interest A. Edel, Y. Song, T. Wiewelhove and A. Ferrauti declare that they have no competing interests.

For the present contribution the authors did not perform any studies with human participants or animals. For the studies discussed in this contribution apply the ethical guidelines statements as declared in the respective publications.

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