Physical demands of tennis across the different court surfaces, performance levels, and sexes: a systematic review with meta-analysis

Running heading: Physical demands of tennis

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ABSTRACT

Background

Tennis is a multidirectional, high-intensity intermittent sport for males and females, played across multiple surfaces. Although several studies have attempted to characterise the physical demands of tennis, a meta-analysis is still lacking.

Objective

To describe and synthesise the physical demands of tennis across the different court surfaces, performance levels, and sexes.

Methods

PubMed, Embase, CINAHL, and SPORTDiscus were searched from inception to April 19th, 2022. A backward citation search was conducted for included articles using Scopus.

The PECOS framework was used to formulate eligibility criteria. Population: tennis players of regional, national or international playing levels (juniors and adults). Exposure: singles match play. Comparison: sex (male/female), court surface (hard, clay, grass). Outcome: duration of play, on-court movement, and stroke performance. Study design: cross-sectional, longitudinal.

Pooled means or mean differences with 95% confidence intervals were calculated. A random-effects meta-analysis with robust variance estimation was performed. The measures of heterogeneity were Cochrane Q and 95% prediction intervals. Subgroup analysis was used for different court surfaces.

Results

The literature search generated 7736 references; 64 articles were included for qualitative and 42 for quantitative review. Mean [95% CI] rally duration, strokes per rally, and effective playing time on all surfaces were 5.5s [4.9, 6.3], 4.1 [3.4, 5.0], and 18.6% [15.8, 21.7] for international male players and 6.4s [5.4, 7.6], 3.9 [2.4, 6.2], and 20% [17.3, 23.3] for international female players. Mean running distances per point, set, and match were 9.6m [7.6, 12.2], 607m [443, 832], and 2292m [1767, 2973] (best-of-5) for international male players and 8.2m [4.4, 15.2], 574m [373, 883], and 1249m [767, 2035] for international female players. Mean first and second serve speeds were 182 $km \cdot hr^{-1}$ [178, 187] and 149 $km \cdot hr^{-1}$ [135, 164] for international male players and 156 $km \cdot hr^{-1}$ 95%CI [151, 161] and 134 $km \cdot hr^{-1}$ [107, 168] for international female players.

Conclusions

The findings from this study provide a comprehensive summary of the physical demands of tennis. These results may guide tennis-specific training programmes. We recommend more consistent measuring and reporting of data to enable future meta-analysts to pool meaningful data.

The protocol for this systematic review was registered a priori at the Open Science Framework (Registration DOI: 10.17605/OSF.IO/MDWFY)

Key Points:

The mean match duration (best-of-3 sets) was around 1.5 hours for international male and female players (all surfaces) and approximately 75 minutes for junior national male and female players (hard court).

The mean rally duration of international players was shortest on grass court with 4.3s 95% CI [3.1, 5.9] for males and 5.7s [4.8, 6.7] for females, followed by hard court with 5.6s [4.9, 6.5] and 6.4s [5.0, 8.1s], and clay court with 7.1s CI [6.2, 8.1] and 8.8s [5.2, 15.0].

The mean effective playing time was around 1/5th of the actual playing time in international male and female players and roughly 1/4th in junior national players of both sexes.

The mean first and second serve speeds were higher in international male players (182 $km\cdot hr^{-1}$ [178, 187] and 149 $km\cdot hr^{-1}$ [135, 164]) than in female players (156 $km\cdot hr^{-1}$ 95%CI [151, 161] and 134 $km\cdot hr^{-1}$ [107, 168]), and mean first serves speeds were higher than second serve speeds.

1. Introduction

Tennis is a multidirectional, high-intensity intermittent sport for males and females, played across multiple indoor and outdoor surfaces. Globally, over 87 million people play tennis, of which 59% are male and 41% female [1]. The three main playing surfaces in tennis are hard court, clay court, and grass court [2].

Tennis requires technical and tactical proficiency, mental skills, and high physical performance levels for players to excel[3-5]. Elite tennis players need to perform both endurance and strength training to produce powerful strokes and handle the high intensities of play, including the many rapid accelerations, decelerations and changes of directions that occur over the length of a match (one or more hours) [3, 6]. .

Understanding the physical demands of tennis during match play is vital for developing young players and preparing elite players for competition [3]. However, the external loads are hard to generalise due to the unpredictable and varied nature of the sport and match play. For example, the duration of a tennis match is a crucial variable [7] but can vary greatly. Many factors influence match duration, including the scoring system (e.g., no-advantage scoring) [8, 9], match format (e.g., best-of-3 or best-of-5 sets), the quality of the opponent, and the playing surface and type of balls used [10]. These factors likely influence the physical demands of tennis.

Advances in technology, including visual tracking systems and wearable sensors, have made it easier to analyse the specific demands of tennis [11]. Match duration, the number of strokes, and tennis-specific loads (e.g., acceleration, deceleration, change of direction, stroke speed) can now be quantified. These parameters allow a comprehensive overview of the external loads of tennis. Although there are substantial differences between matches, synthesising the data using meta-analysis can provide valuable insights into the specific loads players encounter and manage.

Therefore, we aimed to describe and synthesise the physical demands of tennis. We reviewed the data across the different playing surfaces (clay, hard, and grass court), performance levels (regional, national and international), and sex of tennis players (male and female).

2. Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [12] guided the reporting of this systematic review (Online Resource 1). We registered the protocol for this systematic review a priori at the Open Science Framework (Registration DOI: 10.17605/OSF.IO/MDWFY).

2.1 Eligibility Criteria

The PECOS (Population, Exposure, Comparison, Outcome, and Study design) framework was used to define inclusion and exclusion criteria.

2.1.1 Inclusion criteria

i) Population: Male and female tennis players of regional, national, or international playing level; juniors (≤ 18 years) and adults;
ii) Intervention: Singles tennis match play according to the International Tennis Federation (ITF) Association of Tennis Professionals (ATP), or Women's Tennis Association (WTA) rules;
iii) Comparison: Sex (male/female), court surface (hard, clay, grass);
iv) Outcome: Data collected included at least one parameter related to the duration of play (e.g., strokes, rallies, games, sets, and matches), on-court movement (e.g., accelerations, decelerations, changes of direction, distance covered, and running speed), or stroke performance (count and speed);
v) Study designs: Cross-sectional, longitudinal.

Exclusion criteria:
i) Editorials, notes, letters, case reports, and reviews;
ii) Articles on tennis during match play with modified rules (e.g., time-limited matches);
iii) Articles reporting on wheelchair tennis or doubles tennis;
iv) Articles providing physiological or biomechanical variables only.

2.2 Data Sources and Searches

A systematic literature search was performed in the bibliographic databases PubMed, Embase, CINAHL (via Ebsco), and SPORTDiscus (via Ebsco) from inception to April 19th, 2022. The search syntax was designed by a medical information specialist (LS) with input from two authors (MJ and BP). Search terms included controlled terms (MeSH in PubMed and Emtree in Embase, CINAHL Headings in CINAHL and Thesaurus terms in SPORTDiscus) and free-text terms. The following terms were used (including synonyms and closely related words) as index terms or free-text words: 'tennis' and search terms comprising 'athletic performance'. The search was performed without date or language restrictions. Duplicate articles were excluded by LS using Endnote X20.0.1 (Clarivate™), following the Amsterdam Efficient Deduplication (AED) method [13] and the Bramer method [14]. Additionally, a backward citation search was conducted for included articles using Scopus. The entire search strategy for all databases is detailed in Online Resource 2.

2.3 Study Selection

Four pairs of reviewers (MJ and ML, MJ and BP, BP and SW, and SW and ML) independently screened all potentially relevant titles and abstracts for eligibility using Rayyan [15]. If deemed appropriate, the full-text article was checked for the eligibility criteria. Differences in judgement were resolved through a consensus procedure, and an independent reviewer (FCLO) was available to make a final decision if the reviewer pairs did not reach a consensus. The same four teams of independent reviewers conducted a full-text review of the screened articles to confirm eligibility. Disagreements regarding inclusion were resolved through discussion between reviewers, and once again, an independent reviewer (FCLO) was available to make final decisions if needed. The reviewers documented the reasons for exclusion at each stage.

2.4 Data Extraction

Two reviewers (BP and MJ) independently extracted the following data related to the characteristics of the included studies: name of the first author; the year of publication; country where the study was carried out; study design; study aim; study population; sample size (participants and matches); age; sex (% male); playing level; court surface; the assessment tool; comparison; and an overview of the outcome parameters of each study. Playing level was determined by the level of the tournaments the player participated in, i.e., regional, national, or international, or by their ranking. Court surface was defined by the playing surface of the matches, i.e., hard, clay, or grass.

Table I presents the data on the outcome parameters extracted from the articles. The relevant authors were contacted if data were missing or required clarification.

Table I. Outcome parameters for duration, on-court movement and stroke performance

Duration	**Stroke performance (speed)**
Match duration (min)	Peak serve speed ($km \cdot h^{-1}$)
Rally/stroke duration (s)	First serve speed ($km \cdot h^{-1}$)
Effective playing time* (%)	Second serve speed ($km \cdot h^{-1}$)
Work-to-rest ratio**	Groundstroke speed ($km \cdot h^{-1}$)
Points per game/set/match (#)	Forehand speed ($km \cdot h^{-1}$)
Games per set/match (#)	Backhand speed ($km \cdot h^{-1}$)
Sets per match (#)	
On-court movement	**Stroke performance (count)**
Accelerations per minute/speed zone/match (#)	Strokes per rally/game/set/match/second (#)
Decelerations per minute/speed zone/match (#)	Serves per game/set/match (#)
Direction changes per rally/match (#)	First serves per game/set/match (#)
Distance covered per point/game/set/match (m)	Second serves per game/set/match (#)
Distance covered per speed zone (m)	Forehands per game/set/match (#)
Distance covered per minute (m)	Backhands per game/set/match (#)
Distance covered per speed zone per minute (m)	Forehand volleys per game/set/match (#)
Average running speed ($m \cdot s^{-1}$)	Backhand volleys per game/set/match (#)
Peak running speed ($m \cdot s^{-1}$)	Overheads per game/set/match (#)

* Effective playing time is the percentage of the total playing times against the real match time. It consists of the playing time, all the breaks between points, games, and sets, and the rest periods during any other breaks (e.g., injury time out, heat rule, replay by Hawk-Eye [16], and discussion with chair umpire). **The work-to-rest ratio is the ratio between rally duration and the rest periods between rallies and expressed as a quotient.

2.5 Methodological Quality Assessment

Two reviewers (BP and SW) independently assessed the methodological quality of all included studies using the Joanna Briggs Institute checklist for analytical cross-sectional studies [17]. The non-analytical nature of the included studies required minor modifications to the checklist with the removal of item three ("Was the exposure measured in a valid and reliable way?") and the separation of item 2 ("Were the study subjects and the setting described in detail?") to assess descriptions of study participants and study settings separately. Therefore, the modified checklist comprised eight items, including questions on study inclusion criteria, participants, the setting, the condition, confounding factors, validity and reliability of the measurement technique, and appropriate statistical analysis. Each question was rated as 'yes', 'no', or 'unclear'. The reviewers discussed differences until they reached a consensus. The quality assessment outcome was not used to determine study inclusion or perform sub-group analysis based on methodological quality or risk of bias.

2.6 Data Synthesis

The outcomes were analysed based on three overall categories: "male", "female", and "male vs female". We separated our analysis based on experience level, "national" or "international", to ensure reasonable (statistical) homogeneity of the studies.

For quantitative statistical analysis, pooled means or mean differences with 95% confidence intervals (CI) were calculated for movement variables reported by three or more studies. A random-effects meta-analysis was performed with robust variance estimation to account for the dependence of the study means [18, 19]. We calculated a pooled mean or mean difference from the studies using the inverse variance method for pooling [20]. Measures of means were log-transformed for analysis and then back-transformed to ensure no implausible (i.e., negative) estimates were obtained [21]. The standard error of the log-transformed mean was calculated with the formula $\sqrt{\frac{SD^2}{n*mean^2}}$ [22].

The measures of heterogeneity used were Cochrane Q and the resulting chi-squared statistic, I^2 statistic, and 95% prediction intervals (PI). A 95% PI estimates where the actual effects are expected for 95% of similar studies that may be conducted in the future. The estimate of the PI is imprecise if the number of studies is low [23].

We assumed a correlation value of $\rho = 0.8$ for all analyses if correlation values were missing. We performed all calculations and graphics with the software R [24] and the extension packages 'metafor' [25] and 'robumeta' [19].

2.7 Qualitative Synthesis

We summarised the descriptive characteristics of each study and presented these in summary tables and text.

2.7.1. Subgroup analysis

We considered the impact of the three main court surfaces used in tennis: hard court, grass court, and clay court.

2.7.2 Sensitivity Analysis

As correlation values were unknown, a sensitivity analysis with a range of different correlation parameters was performed (ρ = 0, 0.2, 0.4, 0.6, 1.0). Missing standard deviations were imputed as the median value of the included standard deviations in the corresponding analysis [26]. Sensitivity analyses were calculated without the studies with the imputed standard deviation.

3. Results

3.1 Search

The literature search generated 7736 references: 1925 in PubMed, 2056 in Embase, 1149 in CINAHL, and 2606 in SPORTDiscus. After removing duplicates, 4162 papers remained. Based on reviewing the titles and abstracts, 155 articles that dealt with participants playing singles tennis matches and reported on the external loads of tennis (duration of play, on-court movement, or stroke performance) were selected. After the full-text screening, a further 91 articles were excluded, leaving 64 articles for the review, of which 42 articles were included in the quantitative synthesis (meta-analysis) (Figure 1).

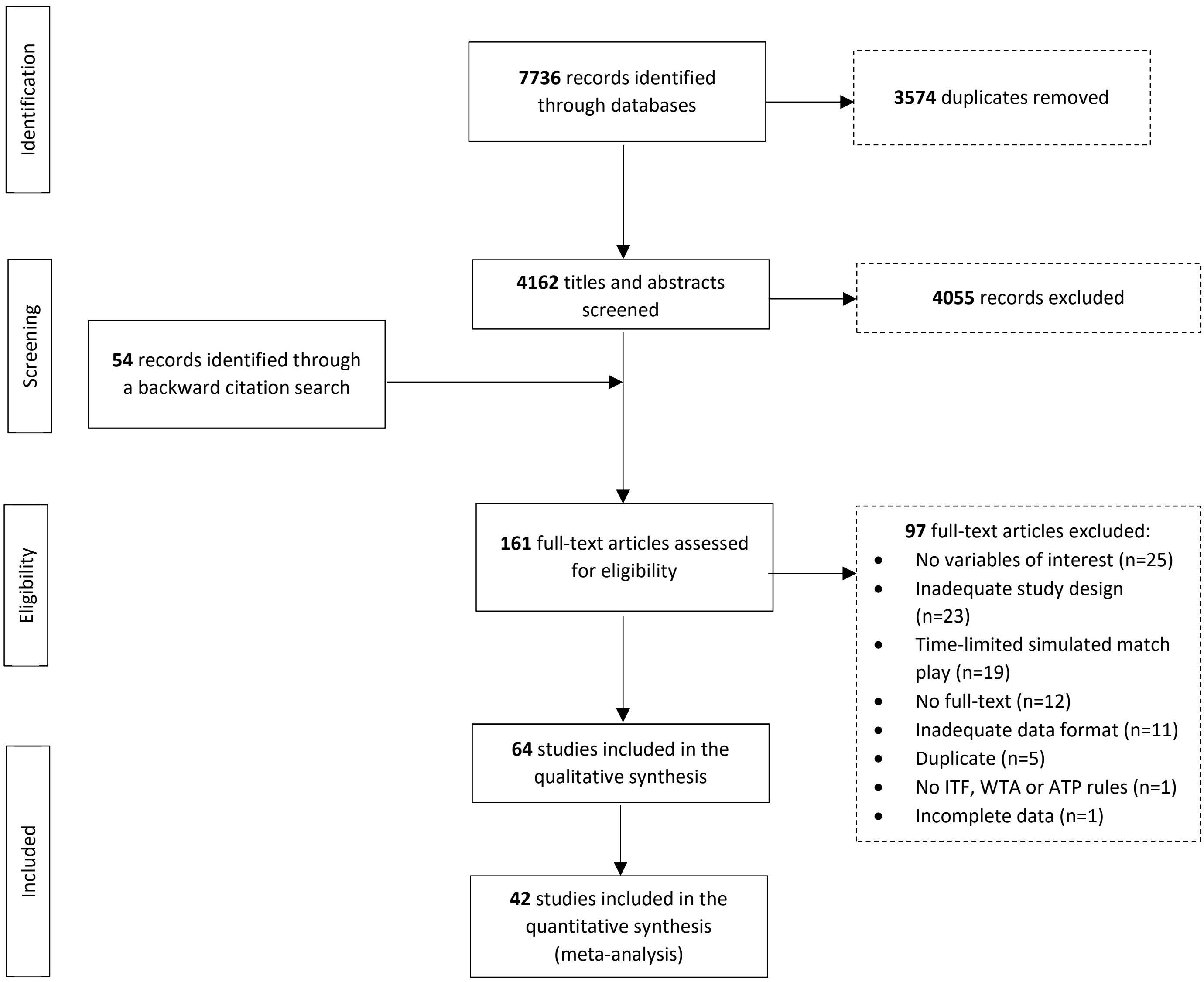

Figure 1. Flow chart of the screening process. *ATP* Association of Tennis Professionals, *ITF* International Tennis Federation, *WTA* Women's Tennis Association.

3.2 Characteristics of the Included Studies

The characteristics of the included articles are presented in Online Resource 3. Most articles were either analytical (n = 46 studies) or descriptive (n=10) cross-sectional studies. There were three pre-post studies, two cross-over trials, two repeated measures experimental designs, and one randomised controlled trial. Most research came from Spain (n=20), followed by Australia (n=11), the United Kingdom (n=8), and the Czech Republic (n=5). The sample size ranged from 8 to 1188 players and 7 to 6984 matches, with one large study analysing 3715 best-of-5-set and 16246 best-of-3-set matches. Most studies included international-level players (n=44), followed by national-level (n=18) and regional-level (n=2). International-level players were primarily adults, whereas national-level players were mainly adolescents. More studies included male players (n=30) than female players (n=7), and 27 had both sexes.

Most studies assessed physical demands on hard court (n= 48), followed by clay court (n= 26), grass court (n=19) and wood (n=1). Regarding duration, rally and match duration were studied most often (n=25), followed by the work-to-rest ratio (n=14), effective playing time (n=13), and rally pace (n=6). From the on-court movements, distances covered (per match, set, game, point, or minute) were studied most often (n=26), followed by average (n=13) and peak running speed (n=12), accelerations (n=7), changes of direction (n=4), and decelerations (n=3). The most frequently assessed stroke counts were strokes per rally (n=15), followed by strokes per match (n=3), per game (n=3), per minute (n=2), and per second (n=1). Serve speed was reported by five studies. Assessment tools used were video analysis (n= 26), followed by a Global Positioning System (GPS) (n=16), match statistics (n=16), Hawk-Eye [16] (n=5), live observation (n=3), and live analysis with a computerised scorebook (n=2). Three studies used video analysis and GPS, and one study used match statistics and Hawk-Eye.

3.3 Methodological Quality Assessment

The overall (modified) Joanna Briggs Institute checklist scores ranged from 3/8 (37.5%) to 8/8 (100%) points (Table II).

Table II. (Modified) Joanna Briggs Institute (JBI) checklist score (%) of the studies included in this review (n=64).

	Item number and corresponding score								Yes	No	Unc lear	JBI Checklist Score
Author(s) (year)	**1**	**2a**	**2b**	**4**	**5**	**6**	**7**	**8**				
Bergeron et al. (2007) [27]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Brown & O'Donoghue (2008) [28]	N	N	Y	Y	Y	Y	Y	N	5	3	0	62.5
Brown (2021) [29]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Carboch (2017) [30]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Carboch & Plachá (2018) [31]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Carboch et al. (2018) [32]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Carboch et al. (2019) [33]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Carboch et al. (2020) [34]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Cui et al. (2017) [35]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5

Cui et al. (2018) [36]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Cui et al. (2020a) [37]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Cui et al. (2020b) [38]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Fernández-Elias et al. (2020) [39]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87,5
Fernandez-Fernandez et al. (2007) [40]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87,5
Fernandez-Fernandez et al. (2008) [41]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87,5
Filipcic et al. (2015) [42]	Y	N	Y	Y	Y	N	Y	Y	6	2	0	75,0
Filipcic et al. (2021) [43]	N	Y	Y	Y	Y	N	Y	Y	6	2	0	75,0
Fitzpatrick et al. (2019) [44]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87,5
Galé-Ansodi et al. (2014) [45]	Y	U	Y	Y	N	Y	Y	N	5	2	1	62,5
Galé-Ansodi et al. (2016) [46]	N	N	Y	Y	N	N	U	Y	3	4	1	37,5
Galé-Ansodi et al. (2017a) [47]	N	Y	Y	Y	Y	Y	U	U	5	1	2	62,5
Galé-Ansodi et al. (2017b) [48]	N	N	Y	Y	Y	Y	Y	Y	6	2	0	75,0
Galé-Ansodi et al. (2018) [49]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87,5
Gallo-Salazar et al. (2015) [50]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	100.0
Gallo-Salazar et al. (2019) [51]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	100.0
Giles et al. (2021) [52]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Hoppe et al. (2014) [53]	Y	Y	Y	U	Y	Y	Y	Y	7	0	1	87.5
Hoppe et al. (2016) [54]	N	Y	Y	U	Y	Y	Y	Y	6	1	1	75.0
Hornery et al. (2007) [55]	N	Y	Y	Y	Y	Y	Y	U	6	1	1	75.0
Johnson & McHugh (2005) [56]	N	N	Y	Y	N	N	Y	N	3	5	0	37.5
Kilit & Arslan (2017) [57]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Kilit & Arslan (2018) [58]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Klaassen et al. (1998) [59]	N	N	Y	Y	Y	Y	U	Y	5	2	1	62.5
Kovalchik & Reid (2017) [60]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Lisi & Grigoletto (2021) [9]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Mackie et al. (2013) [61]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Maquirriain et al. (2016) [62]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Martínez-Gallego et al. (2013)	N	U	Y	Y	Y	Y	Y	Y	6	1	1	75.0
Martínez-Gallego et al. (2019)	N	U	Y	Y	Y	Y	Y	Y	6	1	1	75.0
McCarthy et al. (1998) [63]	N	Y	Y	Y	N	Y	Y	Y	6	2	0	75.0
Meffert et al. (2019) [64]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Mendez-Villanueva et al. (2007) [65]	N	Y	Y	N	N	Y	Y	Y	5	3	0	62.5
Morante & Brotherhood (2005) [66]	Y	N	Y	Y	Y	Y	Y	U	6	1	1	75.0
Moreno-Pérez et al. (2019) [67]	U	Y	Y	Y	Y	Y	Y	Y	7	0	1	87.5
Murphy et al. (2016) [68]	N	Y	Y	Y	Y	N	N	Y	5	3	0	62.5
Myers et al. (2016) [69]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
O'Donoghue & Ingram (2001) [70]	N	N	Y	Y	Y	Y	Y	Y	6	2	0	75.0

O'Donoghue & Liddle (1998) [71]	N	N	Y	Y	Y	Y	U	U	4	2	2	50.0
Pereira et al. (2017) [72]	N	N	Y	Y	Y	N	Y	Y	5	3	0	62.5
Pereira et al. (2016) [73]	N	U	Y	Y	Y	Y	Y	Y	6	1	1	75.0
Perri et al. (2018) [74]	U	Y	Y	Y	Y	Y	Y	U	6	0	2	75.0
Ponzano et al. (2017) [75]	N	Y	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Reid et al. (2016) [76]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Reilly & Palmer (1994) [77]	N	Y	Y	Y	N	N	Y	Y	5	3	0	62.5
Sánchez-Pay et al. (2021) [78]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Smith et al. (2018a) [79]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	100.0
Smith et al. (2018b) [80]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	100.0
Stare et al. (2015) [81]	N	Y	Y	Y	Y	Y	Y	N	6	2	0	75.0
Takahashi et al. (2006) [82]	N	N	Y	Y	Y	Y	Y	Y	6	2	0	75.0
Takahashi et al. (2009) [83]	N	N	Y	Y	Y	Y	Y	Y	6	2	0	75.0
Torres-Luque et al. (2011) [84]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	100.0
Yusoff & Krasilshchikov (2021) [85]	N	N	N	Y	N	N	Y	Y	3	5	0	37.5
Whiteside & Reid (2017) [86]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Whiteside et al. (2015) [87]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	87.5
Number of studies applying the item	27	29	63	61	57	56	59	55				

Questions from the JBI Checklist: 1. Were the criteria for inclusion in the sample clearly defined? 2a. Were the study subjects described in detail? 2b. Was the setting described in detail? 4. Were objective, standard criteria used for measurement of the condition? 5. Were confounding factors identified? 6. Were strategies to deal with confounding factors stated? 7. Were the outcomes measured in a valid and reliable way? 8. Was appropriate statistical analysis used? *N* No, *U* Unclear, *Y* Yes

Among the 64 studies assessed, almost all (63/64; 98%) described the study setting in detail (item 2b), and 61/64 (95%) studies used objective and standard criteria for measuring the conditions (item 4). Most studies adequately identified the confounding variables (57/64; 89%, item 5), the strategies used to manage them (56/64; 88%, item 6) and used valid and reliable outcome measures (59/64; 92%, item 7). Only 42% of studies (27/64) reported the criteria used for inclusion in their research (item 1), and only 45% clearly described the participants (29/64, item 2a). Most studies (55/64, 85%) used appropriate statistical analyses.

3.4 Quantitative Synthesis (Meta-analysis)

The data are presented as means or mean differences [95% CI] and for all surfaces with 95% PI. The datasets used for analysis are available in Online Resources 4 to 7, and the meta-analysis is available in Online Resource 8. Authors Brown [29], Reid [60, 76, 79, 80, 87], Stare [81], Carboch [34] and Filipcic [43] all kindly responded to our requests to provide missing data or clarification.

3.4.1 Results of Sensitivity Analyses

All analyses with different correlation parameters *($\rho = 0, 0.2, 0.4, 0.6, 1.0$)* showed no impact on the results.

3.5 Duration of play

3.5.1 Match duration: International level

Too few studies were available for pooling the match duration of best-of-5-set matches in male international players. The mean duration of best-of-3-set matches of international male and female players on all surfaces and on hard court are presented in Table III. There was insufficient information for a separate meta-analysis of match duration on clay and grass courts. The mean match duration (min) of international male players on all surfaces was 89.7 [79.0, 101.9] with a 95% PI of [65.7, 122.5], and on hard court 93.0 [73.1, 118.2], and of female players on all surfaces 88.0 [71.7, 107.9] with a 95% PI of [50.0, 154.7], and on hard court 98.9 [75.7, 129.1].

Three studies observed match duration of international male and female players in the same study. The match duration of best-of-3-set matches on hard court was slightly longer for male than for female players, with a mean difference of 8.8 min 95% CI [1.2, 16.4] and a 95% PI of [1.7, 16.0].

3.5.2 Match duration: National level

The mean match duration of junior national male and female players is presented in Table III. There was no information for match duration on grass court of male players and on clay and grass courts of female players. The mean match duration (min) of national male players on hard court and clay court combined was 78.0 [69.2, 87.9], on hard court 76.6 [64.6, 90.9], on clay court 78.6 [70.3, 87.7], and of female players on hard court 72.7 [48,7, 108.7]. There were no studies on the match duration of adult national-level players.

More details are provided in Online Resource 8.

Table III. Match duration of international and national male and female players on different court surfaces

Outcome (Description)	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (*p* value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
			Match duration (min) - International level				
Men All surfaces Best-of-3	Filipcic et al. (2021) Hornery et al. (2007) Mackie (2013) Stare et al. (2015) Mendez-Villanueva et al. (2007) Moreno-Perez et al. (2019) Yusoff & Krasilshchikov (2021)	7	M: 89.7 (79.0, 101.9)	0.696	(65.7, 122.5)	61.9	M: 91.8 (79.0, 106.8)
Men Hard court Best-of-3	Filipcic et al. (2021) Hornery et al. (2007) Mackie (2013) Moreno-Perez et al. (2019) Stare et al. (2015)	5	M: 93.0 (73.1, 118.2)	NA	(52.9, 163.4)	88.1	M: 96.5 (69.8, 133.4)
Women All surfaces	Sánchez-Pay (2021) Fernandez-Fernandez et al. (2008) Fernandez-Fernandez et al. (2007) Mackie (2013) Morante & Brotherhood (2005)	5	M: 88.0 (71.7, 107.9)	0.77	(50.0, 154.7)	80.3	NA

Women Hard court	Fernandez-Fernandez et al. (2007) Mackie (2013) Morante & Brotherhood (2005) Sánchez-Pay (2021)	4	M: 98.9 (75.7, 129.1)	NA	(55.5, 176.1)	66.8	NA
Men vs. women Hard court	Perri et al. (2016) Stare et al. (2015) Torres-Luque et al. (2011)	3	MD: 8.8 (1.2, 16.4)	0.039	(1.7, 16.0)	0	10.2 (-16.1, 36.5)
Match duration (min) - National level (≤ 18 years)							
Men Hard & clay court	Bergeron et al. (2007) Filipcic et al. (2021) Gallo-Salazar et al. (2019) Hoppe et al. (2014) Kilit & Arslan. (2017) Perri et al. (2016) Ponzano et al. (2017) Stare et al. (2015) Torres-Luque et al. (2011)	9	M: 78.0 (69.2, 87.9)	0.876	(52.5, 115.8)	84.75	M: 78.0 (69.2, 87.9)
Men Hard court	Bergeron et al. (2007) Filipcic et al. (2021) Gallo-Salazar et al. (2019) Perri et al. (2016) Ponzano et al. (2017) Stare et al. (2015) Torres-Luque et al. (2011)	7	M: 76.6 (64.6, 90.9)	NA	(44.13, 133.02)	88.90	M: 76.6 (64.6, 90.9)
Men Clay court	Hoppe et al. (2014) Kilit & Arslan (2017) Ponzano et al. (2017)	3	M: 78.6 (70.3, 87.7)	NA	(61.65, 100.09)	0	NA
Women Hard court	Galé-Ansodi (2017a) Perri et al. (2016) Stare et al. (2015)	4	M: 72.7 (48.7, 108.7)	NA	(27.9, 189.8)	88.9	M: 75.9 (40.6, 141.9)

CI Confidence Interval, *I^2* I-square statistic, *M* Mean, *MD* Mean Difference, *min* minutes, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation

3.5.3 Rally duration: Male players

The mean rally duration (s) of international male players on all surfaces combined was 5.5 [4.9, 6.3] with a 95% PI of [3.3, 9.3]. Rally durations on hard, clay, and grass courts were 5.6 [4.9, 6.5], 7.1 [6.2, 8.1], and 4.3 [3.1, 5.9] (Figure 2).

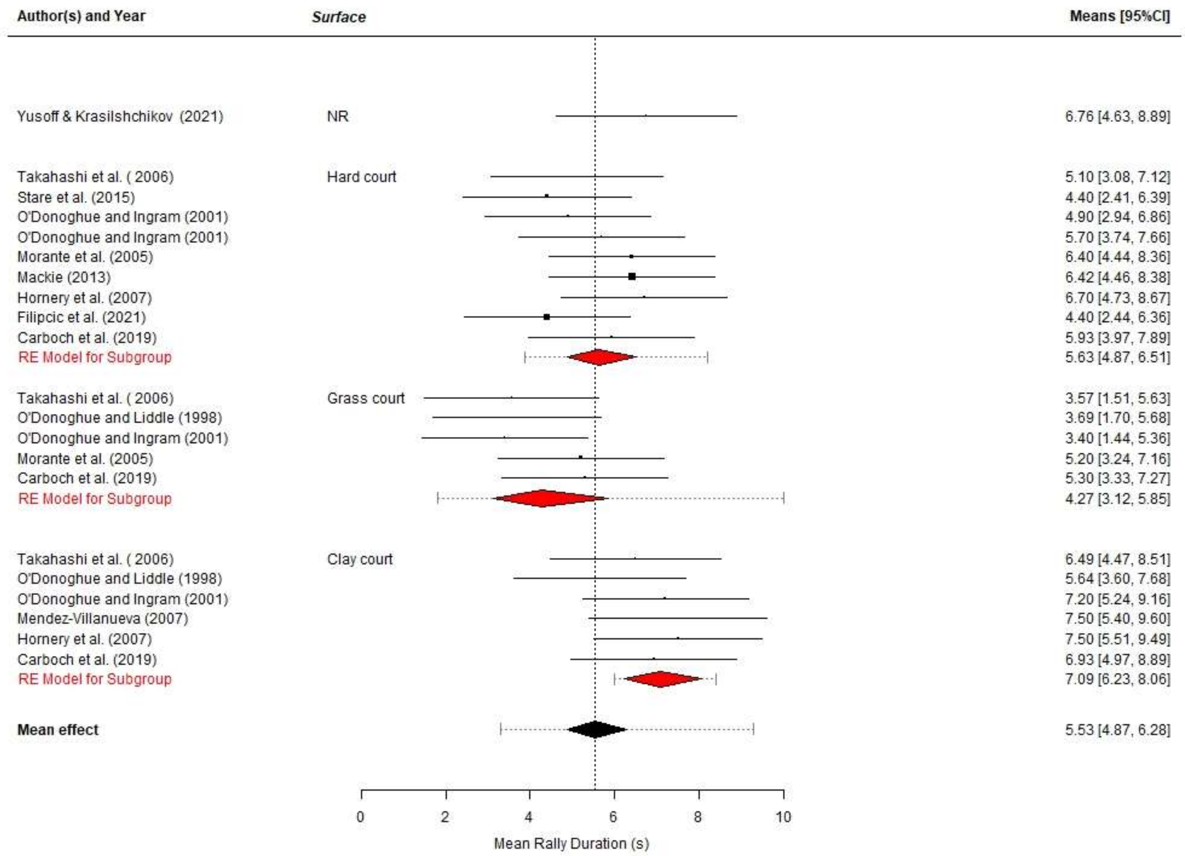

Figure 2. Mean rally duration (s) of International male tennis players on hard, grass, and clay courts. Dashed lines on the forest plot diamonds represent the 95% prediction interval. *RE* Random Effects.

The mean rally duration (s) for junior national male players for hard and clay courts combined was 8.5 [7.2, 10.0s] with a 95% PI of [6.1, 11.9]. The mean rally duration of national male players was 12.0 s [11.4, 12.7] on clay court and 8.3 s [6.9, 10.0] on hard court, with no information available for grass court. There were no data on the rally duration of adult national male players.

3.5.4 Rally duration: Female players

The mean rally duration (s) of international female players on all surfaces was 6.4 [5.4, 7.6] with a 95% PI of [3.7, 11.0]. On hard, clay, and grass courts, rally durations were 6.4 [5.0, 8.1.], 8.8 [5.2, 15.0] and 5.7 [4.8, 6.7] (Figure 3). There were too few studies for pooling rally duration for national-level female tennis players and no studies on the rally duration of adult national female players.

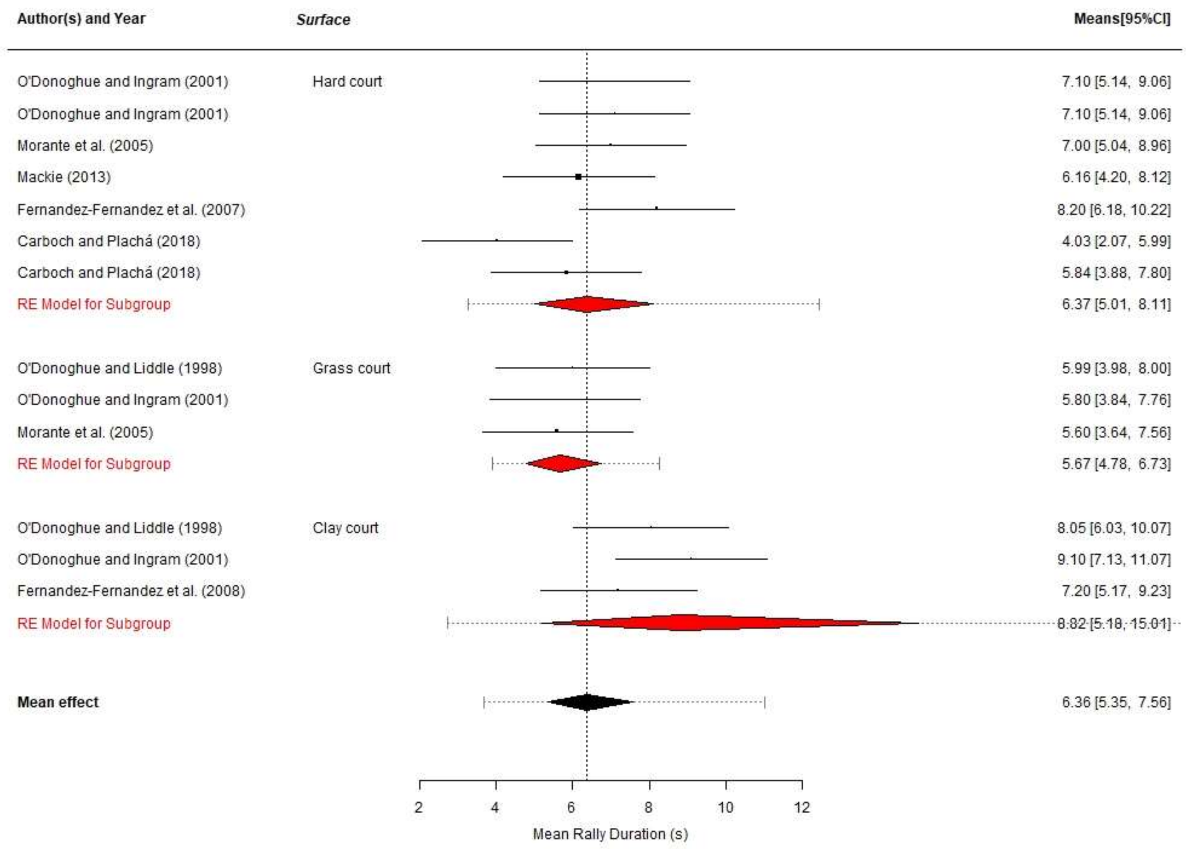

Figure 3. Mean rally duration (s) of international female tennis players on hard, grass, and clay courts. Dashed lines on the forest plot diamonds represent the 95% prediction interval. *RE* Random Effects.

3.5.5. Rally duration: Male vs female players

The mean difference in rally duration (s) of international male and female tennis players on all surfaces was -0.48 [-2.0, 1.0] with a 95% PI of [-3.3, 2.3]. On hard court, clay court and grass court, the mean differences were -0.4 [-2.1, 1.3], -2.0 [-3.9, 0.0], and -1.6 [-5.3, 2.2] (Figure 4). These differences were not statistically significant. More details are provided in Online Resource 8.

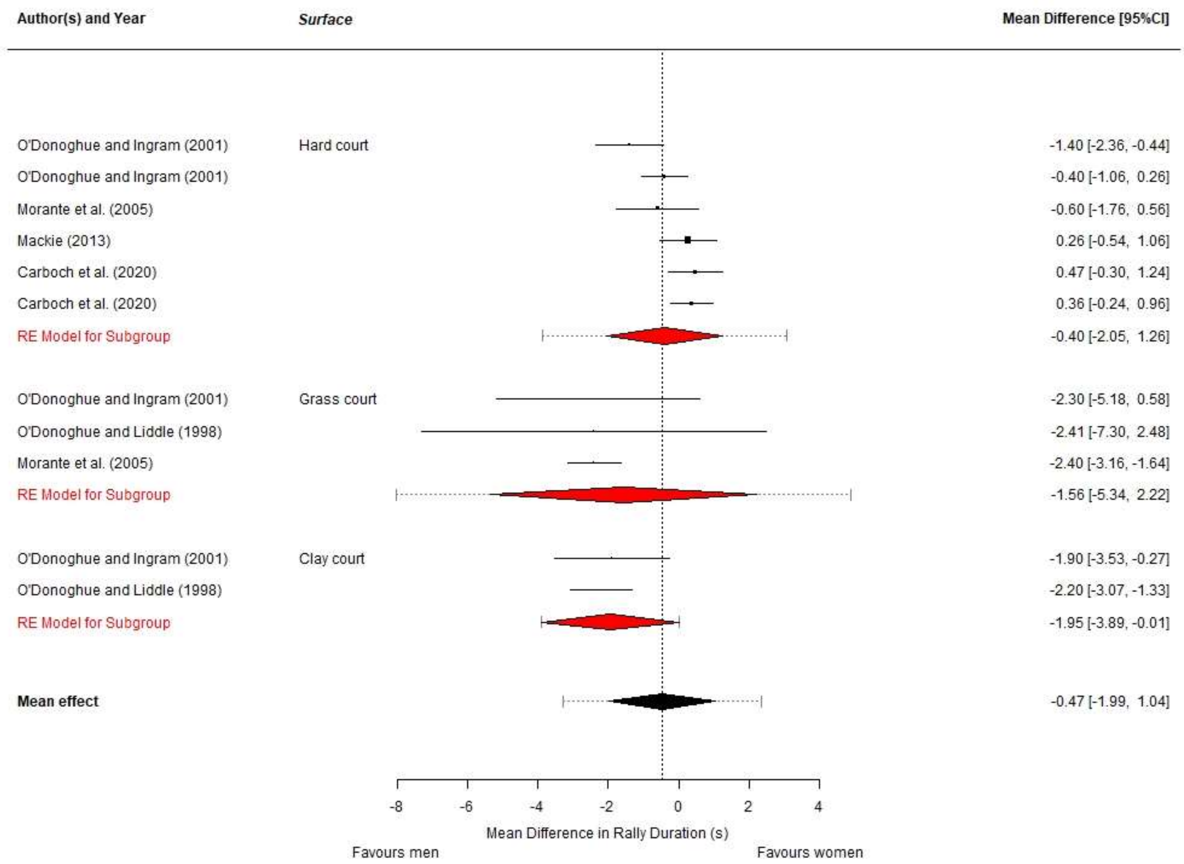

Figure 4. Mean difference in rally duration (s) between international male and female tennis players on hard, grass, and clay courts. A minus sign signifies a shorter mean rally duration favouring male players, and a plus sign favouring female players. Dashed lines on the forest plot diamonds represent the 95% prediction intervals. *RE* Random Effects.

3.5.6 Effective playing time: International level

The mean effective playing time (%) of international male players on all surfaces was 18.8 [15.8, 21.7], with a 95% PI of [11.7, 29.4], and on hard court, 18.2 [15.0, 22.1] (Table IV). The mean effective playing time of female players on all surfaces was 20.0 [17.2, 23.3], with a 95% PI of [13.2, 30.5], and on hard court 20.0 [15.4, 26.1]. There was insufficient information for a separate meta-analysis of male and female players' effective playing time on clay and grass courts.

When comparing the effective playing time of male and female players in the same study, we found no statistically significant differences across all surfaces or during play on hard court. The mean difference on all surfaces was -2.0 [-6.1, 2.1], with a 95% PI of [-10.7, 6.6], and on hard court -1.2 [-4.9, 2.5] (Table IV).

3.5.7 Effective playing time: National level

The mean effective playing time (%) of junior national male players on hard court and clay was 26.2 95% CI [23.3, 29.4], with a 95% PI of [18.4, 37.2], and on hard court 25.6 [21.4, 30.7], with 95% PI [15.8, 41.6] (Table IV). Insufficient information was available for a separate meta-analysis of effective playing time on clay court, and no information was available for grass court. Based on two studies, effective playing time in national female players was 27.1%, based on two studies, with the CI not estimable. There were no data on the effective playing time of adult national-level players. More details are provided in Online Resource 8.

Table IV. Effective playing time of international and national male and female players on different court surfaces

Sex **Court surface**	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (p value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
Effective playing time (%) - International level							
Men All surfaces	Yusoff & Krasilshchikov (2021) Filipcic et al. (2021) Mackie (2013) Mendez-Villanueva et al. (2007) Morante & Brotherhood (2005) O'Donoghue & Liddle (1998) Stare et al. (2015) Whiteside & Reid (2017)	8	M: 18.6 (15.8, 21.7)	0.563	(11.7, 29.4)	90.5	M: 18.9 (15.5, 23.0)
Men Hard court	Filipcic et al. (2021) Mackie (2013) Morante & Brotherhood (2005) Stare et al. (2015) Whiteside & Reid (2017)	5	M: 18.2 (15.0, 22.1)	NA	(10.4, 31.8)	92.5	M: 16.7 (13.2, 21.3)
Women All surfaces	Fernandez-Fernandez et al. (2007) Fernandez-Fernandez et al. (2008) Mackie (2013) Morante & Brotherhood (2005) O'Donoghue & Liddle (1998) Whiteside & Reid (2017)	6	M: 20.0 (17.2, 23.3)	0.469	(13.2, 30.5)	88.6	M: 19.6 (15.2, 25.2)
Women Hard court	Fernandez-Fernandez et al. (2007) Mackie (2013) Morante & Brotherhood (2005) Whiteside & Reid (2017)	4	M: 20.0 (15.4, 26.1)	NA	(10.4, 38.6)	92.3	M: 19.1 (12.6, 28.9)
Men vs women All surfaces	Mackie (2013) Morante & Brotherhood (2005) O'Donoghue & Liddle (1998) Whiteside & Reid (2017)	4	MD: -2.0 (-6.1, 2.1)	0.215	(-10.7, 6.6)	82.6	MD: -1.2 (-7.8, 5.5)
Men vs women Hard court	Mackie (2013) Morante & Brotherhood (2005) Whiteside & Reid (2017)	3	MD: -1.2 (-4.9, 2.5)	0.295	(-6.9, 4.5)	46.3	NA
Effective playing time (%) - National level (≤ 18 years)							
Men Hard & clay court	Filipcic et al. (2021) Gallo-Salazar et al. (2019) Kilit & Arslan (2017) Kilit & Arslan (2018) Stare et al. (2015) Torres-Luques et al. (2011)	6	M: 26.2 (23.3, 29.4)	0.86	(18.4, 37.2)	87.5	M: 25.9 (22.3, 30.1)
Men Hard court	Filipcic et al. (2021) Gallo-Salazar et al. (2019) Kilit & Arslan (2018) Stare et al. (2015) Torres-Luques et al. (2011)	5	25.6 (21.4, 30.7)	NA	(15.8, 41.6)	90.7	M: 25.2 (19.5, 32.5)

CI Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation.

3.6 On-court movement

3.6.1. Distance covered: International level

The Hawk-Eye system only measured distance covered during points and was mainly used for international players.

The mean distances (m) covered across all surfaces by international male players were 2292 [1767, 2973] with 95% PI [1243, 4226] per best-of 5-set match, 607 [443, 831] with 95% PI [279, 1322] per set, and 9.6 [7.6, 12.2] with 95% PI [5.6, 16.6] per point. For female players, these numbers were 1249 [767, 2035] with 95% PI [383, 4071] per best-of-3-set match, 573 [373, 883] with 95% PI not estimable, and 8.3 [4.4, 15.5] with 95% PI [1.7, 40.5](Table V). The distance covered per set in females was based on only two studies. There was insufficient information available for meta-analysis of distance covered by international male players in best-of-3-set matches.

Only the distance covered per best-of-5-set match on all surfaces and hard court could be calculated for male players. There were too few studies for female players to perform a meta-analysis on the distance per surface per match. Distances covered per set and per point were calculated for all surfaces only.

3.6.2. Distance covered: National level

The GPS measured the distance covered during points and moving between points, games and sets. It was primarily used for studies of national players.

The distances (m) covered per match by junior national male players were 3313 [2870, 3826] on hard court and clay, 3200 [2322, 4411] on hard court, and 3272 [3063, 3494] on clay court (Table V). For female players, the distance covered per match was 2967 [2269, 3880] on hard court. The distances covered were reported only for hard court and clay court of male players and for hard court of female players; there was no information for distance covered on grass court.

The mean distance covered per minute on hard court was significantly higher for junior male players than for junior female players, with a mean difference of 2.4 $m.min^{-1}$ [1.4, 3.3].

No information was available for distance covered per set or point by junior national-level players, and no studies on the distance covered by adult national players.

More details are provided in Online Resource 8.

Table V. Distance covered per match, set, point, and minute (m) of international and national male and female players on different court surfaces

Sex **Court surface** **Best-of-3/5**	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (p value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
Distance Covered per Match (m)							
International level							
Men All surfaces Best-of-5	Cui et al. (2020a) Kovalchik & Reid (2017) Maquirriain et al. (2016) Reid et al. (2016)	4	M: 2292.3 (1767.4, 2973.1)	0.533	(1243.4, 4226.2)	85.2	M: 2382.1 (1567.5, 3620.1)
Men Hard court Best-of-5	Cui et al. (2020a) Kovalchik & Reid (2017) Reid et al. (2016)	3	M: 2164.3 (1775.4, 2638.4)	NA	(1372.68, 3412.53)	26.8	M: 2189.4 (1401.5, 3420.3)
Women All surfaces Best-of-3	Cui et al. (2018) Kovalchik & Reid (2017) Reid et al. (2016)	3	M: 1249.1 (766.6, 2035.4)	NE	(383.2, 4071.4)	87.0	M: 1304.8 (652.4, 2609.4)
National level (≤ 18 years)							
Men Hard & clay court Best-of-3	Filipcic, 2021 Galé-Ansodi et al. (2017b) Gallo-Salazar et al. (2019) Hoppe et al. (2014) Hoppe et al. (2016) Kilit & Arslan (2017) Kilit & Arslan (2018) Perri et al. (2018)	8	M: 3313.6 (2870.1, 3825.7)	0.886	(2247.9, 4884.6)	85.6	NA
Men Hard court Best-of-3	Filipcic (2021) Galé-Ansodi et al. (2017b) Gallo-Salazar et al. (2019) Kilit & Arslan (2018) Perri et al. (2018)	5	M: 3200.7 (2322.3, 4411.4)	NA	(1363.1, 7515.5)	92.7	NA
Men Clay court Best-of-3	Hoppe et al. (2014) Hoppe et al. (2016) Kilit & Arslan (2017) Kilit & Arslan (2018)	4	M: 3272.3 (3063.7, 3495.0)	NA	(2940.5, 3641.5)	0	NA
Women Hard court Best-of-3	Galé-Ansodi et al. (2017a) Galé-Ansodi et al. (2017b) Perri et al. (2018)	3	M: 2966.8 2268.6, 3879.8)	NA	(1473.1, 5975.1)	67.7	NA
Distance Covered per Set (m)							
International level							
Men All surfaces	Cui et al. (2020a) Pereira et al. (2017) Reid et al. (2016)	3	M: 607.0 (443.1, 831.5)	0.218	(278.6, 1322.6)	78.1	NA
Women All surfaces	Cui et al. (2020a) Reid et al. (2016)	2	M: 573.6 (372.7, 882.7)	NE	NE	84.7	NA
Distance covered per Point (m)							
International level							
Men All surfaces	Cui et al. (2020a) Filipcic (2021) Kovalchik & Reid (2017) Martínez-Gallego et al. (2019) Pereira et al. (2017) Whiteside et al. (2015)	6	M: 9.6 (7.6, 12.2)	0.925	(5.56, 16.57)	93.7	M: 9.5 (8.2, 11.0)

Men Hard court	Cui et al. (2020a) Filipcic (2021) Kovalchik & Reid (2017) Martínez-Gallego et al. (2019) Whiteside et al. (2015)	5	M: 9.7 (7.6, 12.3)	NA	(5.6, 16.8)	94.5	M: 9.5 (8.3, 11.0)
Women All surfaces	Cui et al. (2018) Kovalchik and Reid (2017) Reid et al. (2016)	3	M: 8.2 (4.4, 15.2)	NE	(1.70, 39.79)	96.7	9.4 (5.3, 16.7)
Women Hard court	Cui et al. (2018) Kovalchik & Reid (2017) Reid et al. (2016)	3	M: 8.3 (4.4, 15.5)	NE	(1.7, 40.5)	96.7	9.44 (4.78 18.63)
Distance covered per Minute (m)							
National level (≤ 18 years)							
Men Hard court	Fernández-Elias et al. (2020) Galé-Ansodi et al. (2017b) Galé-Ansodi et al. (2018) Gallo-Salazar et al. (2019) Perri et al. (2018)	5	M: 48.2 (45.3, 51.3)	NA	(41.5, 56.1)	66.3	NA
Women Hard court	Galé-Ansodi et al. (2017a) Galé-Ansodi et al. (2017b) Galé-Ansodi et al. (2018) Perri et al. (2018)	4	M: 45.4 (41.5, 49.7)	NA	(35.8, 57.7)	87.7	NA
Men vs women Hard court	Galé-Ansodi et al. (2017b) Galé-Ansodi et al. (2018) Perri et al. (2018)	3	MD: 2.4 (1.4, 3.3)	0.0111	(1.5, 3.2)	0	NA

CI Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, *NE* Not Estimable, *PI* Prediction Interval, *SD* Standard Deviation.

3.6.3. Running speed: International level

The average and peak running speed ($m \cdot s^{-1}$) of international male tennis players on hard courts were 2.1 [0.6, 7.6] and 5.5 [4.0, 7.4] (Table VI). No or too few studies were available on average and peak running speed on clay or grass courts in male players. There was insufficient information available for a meta-analysis of the average and peak running speed of international female tennis players.

3.6.4. Running speed: National level

The average and peak running speed ($m \cdot s^{-1}$) on hard court were 1.5 [0.6, 3.9] and 5.1 [4.3, 6.0] for junior national male players, and 2.9 [2.7, 3.1] and 4.2 [3.8, 4.6] for national female players (Table VI). No or insufficient data were available for running speed on grass court for male players and on clay and grass courts for female players. There were no data on the running speed of adult national players.

More details are provided in Online Resource 8.

Table VI. Average and peak running speed ($m \cdot s^{-1}$) of international and national male and female players on hard and clay courts

Outcome (Description)	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (p value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
Average Running Speed ($m \cdot s^{-1}$)							
International level							
Men Hard court	Martínez-Gallego et al. (2019) Martínez-Gallego et al. (20≤) Reid et al. (2016) Filipcic (2021)	3	M: 2.1 (0.6, 7.6)	NA	NE	98.5	M: 2.0 (0.5, 8.4)
National level (≤ 18 years)							
Men Hard and clay court	Filipcic et al. (2021) Galé-Ansodi et al. (2017b) Galé-Ansodi et al (2018) Gallo-Salazar et al. (2019) Hoppe et al. (2014) Hoppe et al. (2016) Kilit & Arslan (2017) Kilit & Arslan (2018)	8	M: 1.1 (0.6, 2.0)	0.0473	(0.2, 7.9)	99.8	NA
Men Hard court	Filipcic et al. (2021) Galé-Ansodi et al. (2017b) Galé-Ansodi et al (2018) Gallo-Salazar et al. (2019) Kilit & Arslan (2018)	5	M: 1.5 (0.6, 3.9)	NA	(0.16, 14.47)	99.8	NA
Men Clay court	Hoppe et al. (2014) Hoppe et al. (2016) Kilit & Arslan (2017) Kilit & Arslan (2018)	4	M:0.7 (0.7, 0.7)	NA	(0.7, 0.7)	0	NA
Women Hard court	Galé-Ansodi et al. (2017a) Galé-Ansodi et al. (2017b) Galé-Ansodi et al (2018)	3	M: 2.9 (2.7, 3.1)	NA	(2.44, 3.43)	30.8	NA
Peak Running Speed ($m \cdot s^{-1}$)							
International level							
International men, hard court	Fernández-Elias et al. (2020) Filipcic (2021) Kovalchik & Reid (2017) Whiteside et al. (2015)	4	M: 5.5 (4.0, 7.4)	NA	(3.0, 10.1)	81.8	M: 5.8 (4.9, 6.9)
National level (≤ 18 years)							
Men Hard and clay court	Filipcic et al. (2021) Galé-Ansodi et al. (2017b) Galé-Ansodi et al (2018) Gallo-Salazar et al. (2019) Hoppe et al. (2014) Hoppe et al. (2016)	6	M: 4.8 (4.3, 5.4)	0.11	(3.6, 6.5)	92.8	NA
Men Hard court	Filipcic et al. (2021) Galé-Ansodi et al. (2017b) Galé-Ansodi et al (2018) Gallo-Salazar et al. (2019)	4	M: 5.1 (4.3, 6.0)	NA	(3.3 7.7)	94.5	NA

CI Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, NE Not Estimable, *PI* Prediction Interval, *SD* Standard Deviation.

3.7 Stroke performance

3.7.1. Strokes per rally: International level

The mean number of strokes per rally for international male players was 4.1 [3.4, 5.0] with a 95% PI of [2.5, 6.9] on all surfaces, 4.2 [3.4, 5.3] on hard court, and 4.8 [3.4, 6.7] on clay court (Table VII). The mean number of strokes of female players was 3.9 [2.4, 6.2] with a 95% PI of [1.5, 9.8] on hard and clay courts combined. There were insufficient data available for a separate meta-analysis of strokes per rally on grass court in male players and on any surface in female players.

Table VII. Strokes per rally of international and national male and female players on different court surfaces

Outcome (Description)	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (p value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
Strokes per rally (#) - International							
Men All surfaces	Carboch et al. (2019) Filipcic et al. (2021) Hornery et al. (2007) Kovalchik & Reid (2017), Mendez-Villanueva (2007) Stare et al. (2015) Takahashi et al. (2006) Yusoff & Krasilshchikov (2021)	8	M: 4.1 (3.4, 5.0)	0.716	(2.5, 6.9)	82.7	M: 4.1 (3.2, 5.2)
Men Hard court	Carboch et al. (2019) Filipcic et al. (2021) Hornery et al. (2007) Kovalchik & Reid (2017) Takahashi et al. (2006) Stare et al. (2015)	6	M: 4.2 (3.4, 5.3)	NA	(2.4, 7.5)	89.2	M: 4.3 (3.1, 5.9
Men Clay court	Carboch et al. (2019) Hornery et al. (2007) Mendez-Villanueva (2007) Takahashi et al. (2006)	4	M: 4.8 (3.4, 6.7)	NA	(2.5, 9.2)	48.4	NA
Women Hard and clay courts	Carboch et al. (2018) Fernandez-Fernandez et al. (2007) Fernandez-Fernandez et al. (2008) Kovalchik & Reid (2017)	4	M: 3.9 (2.4, 6.2)	0.0415	(1.5, 9.8)	71.6	M: 3.3 (1.3, 8.2)
Strokes per rally (#) – National (≤ 18 years)							
Men Hard and clay court	Gallo-Salazar et al. (2019) Kilit & Arslan (2017) Kilit & Arslan (2018) Stare et al. (2015) Torres-Luque et al. (2011	5	M: 4.9 (3.2,7.50)	0.328	(1.7, 14.1)	99.0	M: 4.9 (2.7, 8.9)
Men Hard court	Gallo-Salazar et al. (2019) Kilit & Arslan (2018) Stare et al. (2015) Torres-Luque et al. (2011	4	M: 4.6 (2.6, 8.2)	NA	(1.2, 18.0)	99.3	M: 4.4 (1.6, 12.1)

CI Confidence Interval, I^2 I-square statistic, *M* Mean, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation, *#* number.

3.7.2. Strokes per rally: National level

In junior national male players, the mean number of strokes per rally was 4.9 [3.2, 7.5] for hard and clay courts combined with a 95% PI of [1.72, 14.10], 4.6 [2.6, 8.2] for hard court, 6.5 [1.7, 25.2] for clay court, and with no data for grass court (Table VII). In junior female players, the mean number of strokes per rally was 4.8 [1.1, 21.8}, based on two studies. There were no data on adult national players. More details are provided in Online Resource 8.

3.7.3. Serve speed: International level

The mean first and second serve speed (km·h^{-1}) on all surfaces were 182 [178, 187] and 149 [135, 164] for male players and 156 [151, 161] and 134 [107, 168] for female players (Table VIII). Only two studies were available for meta-analysis of the second serve speed of female players. More details are provided in Online Resource 8.

3.7.4. Serve speed: National level

There were no data on the serve speed of national male and female players.

Table VIII. First and second serve speed (km.h^{-1}) of international male and female players on different court surfaces

Outcome (Description)	**Studies included in the meta-analysis** (author(s), year)	**Number of studies** (n)	**Effect size** (95%CI)	**Test for (Subgroup) Differences** (p value)	**95% PI**	**I²** (%)	**Sensitivity analysis for imputed SDs**
			First Serve Speed (km.h^{-1}) - International level				
Men All surfaces	Cui et al. (2020a) Hornery et al. (2007) Kovalchik & Reid (2017) Reid et al. (2016) Fitzpatrick et al. (2019) Brown et al. (2021)	6	M: 182.4 (178.1, 186.9)	0.099	(171.2, 194.4)	95.3	M: 183.0 (177.9, 188.3)
Men Hard court	Cui et al. (2020a) Hornery et al. (2007) Kovalchik & Reid (2017) Reid et al. (2016)	4	M: 181.9 (176.6, 187.4)	NA	(169.2, 195.6)	84.9	M: 182.7, (174.9, 191.0)
Men Clay court	Cui et al. (2020a) Fitzpatrick et al. (2019) Hornery et al. (2007)	3	M: 180.0 (168.9, 191.9)	NA	(153.8, 210.7)	84.7	NA
Women All surfaces	Kovalchik & Reid (2017) Reid et al. (2016) Fitzpatrick et al. (2019) Brown et al. (2021)	4	M: 156.1 (151.4, 161.0)	NE	(143.7, 169.6)	94.6	M:156.9 (150.0, 164.1)
			Second Serve Speed (km.h^{-1}) - International level				
Men All surfaces	Hornery et al. (2007) Reid et al. (2016) Cui et al. (2020a) Brown et al. (2021)	4	M: 148.9 (135.0, 164.1)	0.268	(121.8, 182.0)	97.4	NA
Men Hard court	Cui et al. (2020a) Hornery et al. (2007) Reid et al. (2016)	3	M: 146.4 (125.3, 171.0)	NA	(99.92, 214.44)	95.8	NA
Women Hard and Grass court	Reid et al. (2016) Brown et al. (2021)	2	M: 133.7 (106.6, 167.7)	NA	NE	95.4	NA

CI Confidence Interval*,* I^2 I-square statistic, *M* Mean, *NA* Not Applicable, *NE* Not Estimable, *PI* Prediction Interval, *SD* Standard Deviation.

3.8 Qualitative (descriptive) synthesis

Best-of-5-set match duration, games per set, points per match, work-to-rest ratio, accelerations, decelerations, changes of directions, serves per game, strokes per game, and groundstroke speeds could not be included in the meta-analysis due to missing data, or because only one or two studies were available per outcome parameter. The main results of these outcome variables are presented below (see Online Resources 4 to 7).

3.8.1. Match Duration

The median match duration (min) in male tennis players was 142 (Q75 179, mean 150) for best-of-5-set matches and 92 (Q75 119, mean 98) for best-of-3-set matches, based on 3712 and 16246 matches, respectively [9]. We identified no study of similar size for female players.

3.8.2. Points, games, and sets

At the four Grand Slams in 2016, the mean number of sets per match, games per set, points per game and points per match were 3.8, 9.8 [9.3,10.3], 6.3 [6.1, 6.5], and 235 in male players (best-of-5), and 2.3, 9.3 [8.8, 9.8], 6.5 [6.3, 6.7], and 143 in female players [30].

At Wimbledon (1992 to 1995), the mean number of sets per match, games per set, points per game, and points per match were 3.7, 9.9, 6.1 and 230 in male players, and 2.3, 8.9, 6.5, and 132 in female players (95%CI not provided) [59].

Kovalchik and Reid [60] reported the median (IQR) number of points per match on the different court surfaces for junior and adult male and female players at the four Grand Slams in 2016, plus the 2017 Australian Open for juniors. The numbers on hard, clay and grass courts for junior male players were 130 (104-167), 131 (112-158), and 137 (118-162), and for junior female players, 122 (105-175), 122 (104-150), and 115 (100-177). For professional male players, these numbers were 216 (177-265), 213 (174-258), and 221 (180-275), and for female players, 129 (108-171), 133 (108-170) and 130 (111-169).

3.8.3 Work-to-rest ratio

In international male tennis players, the mean work-to-rest ratio varied from 1:3.5 to 1:5.6 on hard court [33, 43, 61], 1:2.0 to 1:3.5 on clay court [33, 65, 88] and from 1:3.7 to 1:5.0 on grass court [33, 88]. In national-level male players, the work-to-rest ratio ranged from 1:2.5 to 1:3.7 on hard court [43, 51, 58, 84] and was 1:2.1 on clay court [57, 58].

In international female players, the mean work-to-rest ratio varied from 1:3.4 to 1:4.5 on hard court [31, 61], 1:2.1 to 1:2.4 on clay court [41, 88] and 1:3.2 on grass court [88]. The work-to-rest ratio of national-level female tennis players on hard court was 1:2.2 [84].

Carboch et al.[34] reported an unusually high work-to-rest ratio, ranging from 1:5 to 1:7 in males and females. However, after contacting the author, this turned out to be an error, and we included the correct numbers (ranging from 1:3.2 to 1:4.4) in Online Resource 4.

3.8.4 Accelerations and decelerations

The mean [95%CI] number of accelerations (>1.5m·s^{-2}) and decelerations (<1.5m·s^{-2}) in nine international male tennis players was 18.2 [0, 40.6] and 19.1 [0, 38.9], measured using GPS and accelerometers [39]. The mean number of accelerations per minute (>3m·s^{-2}) in 12 national-level male junior tennis players measured using GPS was 0.3 [0.2, 0.4] in a morning match and 0.2 [0.1, 0.3] in the second match in the afternoon of the same day [51]. The mean number of accelerations (2 to < 4m·s^{-2} and ≥4m·s^{-2}) were 59 [33, 85] and 19 [0, 55] in 20 junior male players, and 62 [20, 104] and 42 [0, 106] in 20 adult regional-level male players, measured using GPS and accelerometers [54].

3.8.5 Changes of Direction

The mean [95%CI] number of changes in directions in 14 international male players was 2.5 [0.7, 4.3] on hard court and 2.4 [0.0, 5.0] on clay court [55], and 2.3 [0.0, 5.1] in eight female players on hard court [40].

At the 2012-2017 Australian Open, the median (IQR) number of changes in direction was 6.0 (0-18) in junior male players (12 matches), 5.0 (0-22) in adult male players (21 matches), 5.0 (0-18) in junior female players (6 matches), and 4.5 (0-18) in adult female players (21 matches) [60]. (See Online Resource 5)

3.8.6 Stroke counts

Whiteside & Reid reported on the number of shots per game in the first four rounds of the 2012-2016 Australian Open tournaments in 18 male and 21 female players [86].

The mean number of strokes per game overall for rounds 1 to 4 were 15.0 [8.9, 21.2], 15.5 [9.0, 22.0], 17.4 [10.1, 24.7] and 18.7 [9.9, 27.4] for male players, and 17.7 [11.5, 23.9], 18.2 [10.9, 25.5], 18.1 [11.9, 42.1], and 19.3 [11.8, 26.9] for female players.

The mean [95%CI] number of first serves per game in rounds 1 to 4 were 5.7 [5.1, 6.9], 5.8 [4.8, 6.9], 6.0 [4.9, 7.2] and 6.7 [4.7, 8.6] for the male players, and 6.6 [4.4, 8.7], 6.5 [5.2, 7.6], 6,5 [5.2, 7.9], and 6.9 [5.2, 8.7] for the female players.

The mean number of second serves per game in rounds 1 to 4 were 2.1 [1.1, 3.0], 2.0 [1.1, 3.0], 2.1 [1.1, 3.1] and 2.4 [1.3, 3.6] for the male players, and 2.2 [1.3, 3.2], 2.4 [1.5, 3.3], 2.3 [1.2, 3.4], and 2.5 [1.3, 3.7] for the female players. Additional data are provided in Online Resource 6.

3.8.7 Stroke speeds

At the 2012-2014 Australian Open, mean peak first serve speeds were 206 km/h [183, 230] for male players and 172 km/h [151, 1993] for international female players [76]. The mean groundstrokes' speeds were 111 [100, 122] and 106 km/h [95, 118] for international male and female players [76]. Additional data are provided in Online Resource 7.

4. Discussion

This systematic review synthesised the available evidence on the physical demands of tennis relating to the duration of play, on-court movement, and stroke performance in national and international-level male and female tennis players on hard, clay, and grass courts. The main findings are summarised in Figure 6.

Figure 5. Summary of the physical demands of tennis in a) international and b) national players.

4.1 Match duration

The mean match duration (best-of-3 sets) of international tennis players was approximately one hour and a half for males and females across all three surfaces. These findings are comparable to the data of Lisi and Grigoletto [9], who reported a median (mean) match duration of 92 (98) minutes for best-of-3-set matches in international male players, based on 16246 men's professional tennis matches. Unfortunately, no such large study was available for female players. The median (mean) match

duration for best-of-5-set matches of international male players across all surfaces was 142 (150) minutes, based on 3712 matches. The mean match duration of junior male and female national players on hard court was around 75 minutes.
Lisi & Grigoletto showed that match duration was broad, with some matches lasting exceptionally long. The 95% quantile (Q95) and 99.9% quantile (Q999) were 154 and 200 minutes for best-of-3-set matches and 233 and 319 minutes for best-of-5-set matches. They used modelling to show how the format of the match can influence duration in best-of-5-set matches. For example, when using the no-advantage scoring system, the match duration dropped from a median of 144 to 132 minutes. When using one service only, the match duration dropped to 114 minutes, and when using both the no-advantage system and one service, the match duration dropped to 106 minutes.

Governing bodies in tennis have taken measures to reduce the exceptionally long match duration in men's tennis at the highest level by introducing new rules and changing the match format. In 2019, they reduced Davis Cup ties from best-of-5-set to best-of-3-set matches [89], and in 2022 the Grand Slam Tournaments jointly announced the 10-point final set tiebreak at six games-all in the fifth set [90]. The no-advantage scoring system was introduced in 2006 on the ATP and WTA tour for doubles but is not used in singles. At the Next Gen ATP Finals, the 21-and-under-season finale, all singles matches are best-of-5-set matches to four (not six) games, with no-ad scoring [91]. In 2022, the ATP tried out new rules at this event to speed up the game even more: they shortened the time in-between points to 15 s and allowed only one sit-down per set (after three games) [91].

Another important factor influencing the score, and hence the match duration, is the quality of the opposition. The more evenly matched the players are (on the day), the more points, games and sets they are likely to play, and the longer their matches will last.

4.2 Rally duration and Rally length (strokes per rally)

Rally duration and rally length (strokes per rally) are strongly associated, and any trends in rally duration will be reflected in strokes per rally and vice versa. Important factors impacting rally duration and rally length include court surface [33, 97], playing style and tactics [94] and ball type and wear [34, 92].

4.2.1 Court surface

Rally duration in international male and female players was longest on clay court (7.1 and 8.8s), followed by hard court (5.6 and 6.4s) and grass court (4.3 and 5.7s), but only the differences in rally duration of male players on grass and clay courts reached statistical significance. The mean number of strokes per rally was 4.1 [3.4, 5.0] for international male players on all surfaces and 3.9 [2.4, 6.4] for female players on hard courts and clay, with no data for females on grass. There appeared to be a trend of more strokes per rally on clay court and fewer strokes on hard court in male players, with insufficient data for grass court. However, no statistically significant differences were found, which may be partly related to the relatively small number of studies in this area.

Players may adjust their playing style according to the court surface, impacting rally duration. Previously, only notational methods were available to study the association between playing style and rally duration on different court surfaces. However, these methods are limited by the amount of data that can be collected and the need to define observable variables in advance [97]. Today's automated ball-tracking systems allow high-volume data collection for post-recording analysis and have provided new insights.

4.2.2 Game characteristics

Carboch compared the game characteristics of international male and female players at the four Grand Slams [30]. He showed that the number of first serves in, points per game and games per set were reasonably similar in male and female players across all surfaces. However, male players won more points after first and second serves (most at Wimbledon), and female players won more return games (Roland Garros, Australian Open). Men finished more points with a winner (Wimbledon, Roland Garros), and women with an unforced error (Roland Garros, Australian Open). The author concluded that the main difference between the sexes was the higher efficiency of the first and second serve in men (highest at Wimbledon) and the advantage of the second serve for the receiver in women's matches (all surfaces).

Fitzpatrick et al.[44] compared game strategy during short (0-4 shots), medium (5-8) and long (>9) rallies during men's and women's matches at Wimbledon and Roland Garros in 2016 and 2017. They showed that for male and female players, points won of 0-4 shot rally length, baseline points won, and first and second serve points won were most strongly associated with success. Forced errors and unforced errors were most strongly associated with losing. The authors concluded that short rallies are prevalent at Wimbledon and Roland Garros and that playing style did not drastically change for either sex when transitioning from clay to grass. They suggested that getting used to the ball-court surface interaction might be more important than focusing on a specific area of their game (such as approach shots or net play) when moving from clay to grass.

In a second study, Fitzpatrick et al.[98] analysed the short points played at Wimbledon's men's and women's matches in 2015-2017. Short points were most prevalent compared to medium and long points and accounted for 72% (men), and 66% (women) of all points played. The most prevalent rally length was one shot (ace, or return error) (46.3 and 36.3%), followed by three shots (both 22.2%), two shots (return-winner or error of server's 2nd stroke, 15.7 and 20.2%), four shots (11.2 and 14.5%), and zero shots (double fault, 4.7 and 6.7%). Both points won of one shot, and two shots were associated with winning matches, and the authors concluded that the serve and serve-return should be prioritised during grass court training. Since short rallies are also prevalent at Roland Garros [44], focusing on the serve and serve-return seems appropriate for all court surfaces.

4.2.3 Ball type

The ITF aimed to slow down the power and speed of serves on hard courts and speed up the games on slow courts [99]. In 2002, the ITF introduced three types of balls according to the pace of the surface. The ITF recommended using a slightly larger ball (type 3) on fast courts to reduce speed. They recommended using a somewhat harder ball (type 1) on slow courts, producing a lower bounce angle and speeding up the game. Brown and O'Donoghue [100] studied the rally duration on hard, clay, and grass courts before and after introducing the different types of balls and reported that the differences in rally duration remained but were reduced in magnitude following the introduction of different balls in 2002.

4.2.4 Sex

When comparing rally duration in male and female players in the same study, we found no statistically significant difference between male and female players on hard court and clay, or across all surfaces, with insufficient studies for grass court. It is important to compare the sexes in the same study to control for confounding factors, and more studies of this type are needed.

4.2.5 Junior national players

The mean rally duration of junior national male players was 8.3s on hard court and 12s on clay, slightly longer than the rally duration of international male players on the same surfaces. Hizan et al.[101] compared game characteristics of junior national and adult international players (professionals). Both juniors and professionals hit approximately 60% of their first serves in. The professionals hit more aces, fewer double faults, and won a higher percentage of points when the first serves were in (73% in professional male players, 65% in professional female players, 55-60% in juniors). The juniors and professionals were comparable in the number of points won after the second serve (35-40%). The professionals won a higher percentage of points when returning second serves. Unfortunately, they did not report rally duration, and further studies on game characteristics and rally duration in junior and adult national players are warranted.

4.2.6 Time trend

Ball types, friction coefficients of court surfaces, fitness levels, and playing styles have changed. It would be therefore be interesting to determine whether there has been a time trend in the rally duration of male and female players over the last 20 years on the different court surfaces. Unfortunately, the number of studies was too low to perform a meaningful random-effects meta-regression.

4.3 Distance covered

The mean distance covered was 2300 m per match for international-level males (best-of-5-sets) and 1250 m for international-level females (best-of-three sets). In contrast, the mean distances covered by junior national-level players were 3300 m for males and 3000 m for females. We recommend caution in comparing the results between national and international players because of the use of different measurement systems. The Hawk-Eye system was mainly used for international players and the GPS for junior national players. Several studies using Hawk-Eye analysis only measured the distance covered during the rally, whereas studies using GPS measured the distance covered during and between points. This may explain part of the difference in distance covered between national and international players.

Two other studies in international male players (best-of-3 sets) confirm previous findings. Filipcic et al. [43] measured the distance covered using the Sagit/tennis tracking system and reported a mean distance of 1776±281 m per match in four matches. They only measured the distance covered during play. Pereira et al. [72] used the GPS and reported a much greater mean distance of 3160±880m during four matches. However, the court surface may also have influenced the outcome because Filipcic et al. studied matches on hard court and Pereira et al. matches on clay.

On the other hand, GPS tends to underreport distance and speed at high-intensity efforts [102]. Therefore, distances measured using GPS are likely lower than those estimated using Hawk-Eye (if Hawk-Eye included the distance covered in between rallies). The distance covered during play (including in-between rallies and during change-of-ends) might be even higher than currently reported.

Reid et al. [76] reported that the mean distance covered per match by 102 male players during the 2012-2014 Australian Open was 2110 ± 839 m. However, when he compared 40 top-ranked to 40 lower-ranked players at these events, the match distances were 3082±1075 and 2498±898 m [87]. This disparity in distance covered from the same event and fundamentally the same era of players appears unusual. It seems plausible that methodological differences or the evolving measurement techniques of the tracking providers can explain this difference. Another explanation would be that higher-ranked players move more continuously and anticipate and make better decisions than their lower-ranked peers [103, 104]. Martínez-Gallego et al.[105] seem to confirm this, showing that game winners covered more distance during the rally, and at a lower speed, than game losers.

4.4 Work-to-rest ratio

The work-to-rest ratio is determined by rally duration and the rest periods between points. Therefore, the rules on time allotted between points greatly influence the work-to-rest ratio, more so than the effective playing time. Up until 2019, the ITF [106] and WTA [107] allowed only 20 s between points, whereas the ATP [108] allowed 25 s between points. The 20s time rule of the ITF resulted in time rule violations for 58.8% of the serves at the Australian Open men's singles event, with only 0.1% of the violations being penalised [109]. In 2018, a time clock was introduced at the US Open to speed up the game and to help the chair umpires enforce the rules regarding the time between points. Rule violations decreased (26.3%), but the average time between points did not (21.6s) [110] compared to previous studies. In 2019, the ITF rules [111] and WTA rules [112] were aligned with the ATP, allowing 25 s between points. The differences in regulations between the organisation and rule changes over time make it difficult to compare the work-to-rest ratios of the different player groups.

The work-to-rest ratios in all studies ranged from 1:2 to 1:4.5. The ratios tended to be higher on hard and grass courts than on clay courts due to the shorter rally duration on hard and grass courts compared to clay courts. They were also higher during international-level than the junior national-level competition, again likely due to the shorter rally duration (and possibly longer rest periods) of international compared to national players.

4.5 Effective playing time

In addition to rally duration and rest periods between points, the effective playing time also takes into account medical time outs (3 minutes for treatment after evaluation), the heat rule (10 minutes between 2nd and 3rd set in ITF and WTA tournaments), and the resting time between change-of-ends (90s) and sets (120s). In our review, the mean effective playing time in international male and female tennis players was around 19% and slightly higher in national-level players at about 26%. This difference can partly be explained by longer rallies and shorter rest periods of national-level players, but it may also be due to fewer opportunities for medical time-outs and other breaks. For example, during televised matches of WTA players, the chair umpire may extend the change of ends and set breaks when necessary [113].

4.6 Running speed

The peak running speed was 5 m.s^{-1} (18 km/h) in international male tennis players and slightly lower in females (4.2 m.s^{-1}, 15.1 km/h). Players spend only a short period and cover a relatively short distance running at high speeds. International male players covered 8.7% of the distance at speeds between 4 to 5 m.s^{-1} and only 4.1% at speeds >5 m.s^{-1} [86]. For female players, these numbers were 5.8% and 1.8%.

In tennis, being the better player does not necessarily require the highest running speed. Whiteside et al. [87] showed that despite higher-ranked players covering more distance (3082±1075m) than lower-ranked players (2498±898m), their mean peak speed was lower (6.1±2.5 vs 6.5±3.7 m.s^{-1}) and their mean average speed was higher (1.3±0.2 vs 1.2±0.2 m.s^{-1}). This suggests that the higher-ranked players move more continuously, whereas the lower-ranked players have to accelerate more.[104]

4.7 Accelerations, decelerations, and changes of direction

The number of accelerations and decelerations in tennis may be a better way to describe load in tennis than the mean and peak running speed because of the increased load on the legs during speed and direction changes. Male and female junior tennis players covered most of the distance during a match on hard court while accelerating or decelerating (89.7%).[47] Unfortunately, it was not possible to synthesise the data of the various studies because the cut-off points for the accelerations and decelerations varied widely (e.g., 1-2 $m.s^{-2}$, >1.5 $m.s^{-2}$, >2 $m.s^{-2}$, 2-4 $m.s^{-2}$, >3 $m.s^{-2}$ and >4 $m.s^{-2}$). We recommend using standardised cut-off points for accelerations and decelerations in tennis for future studies to enable comparisons.

Most studies used GPS to measure accelerations, decelerations, and velocities, except one that used Hawk-Eye [86]. Different measurement techniques may explain some of the differences in the outcomes. Unfortunately, Hawk-Eye data are not publicly available, and in the study by Whiteside et al. [87], it was unclear how they computed the number of high-speed runs (>3 m/s^2) per game, making it difficult to repeat these measurements. There is low accuracy and reliability of GPS devices at high-intensity efforts, which may lead to underreporting of distance and speed and possibly, accelerations and decelerations [102]. In particular, caution is warranted when comparing acceleration indices between different GPS brands [114].

The number of changes of direction ranged from 2 to 6 per rally, and Giles et al.[52] reported more than 400 (females) and 600 (males) changes of direction per match during the Australian Open (2016-2018). These direction changes, combined with the distances covered and the number of accelerations and decelerations, result in a high load on the lower extremities, for which the players must prepare.

4.8 Serve speed

The serve speed of international male players was higher than that of female players, and the mean first serve speed was higher than the mean second serve speed in both males and females. We did not find data on serve speed in national male or female players.

The serve is an important stroke in tennis, and players win more points when serving than receiving across all surfaces.[29] The success rate is higher in males than females, and higher after the first than after the second serve.[115] The overall success rate of the serve during singles matches at Wimbledon from 2004-2019 was 75% and 57% for male players' first and second serve and 66% and 53% for female players.[29] Serve speed, and the chance of winning the point are correlated, both in males and females and after the first and second serve. Other factors determining a server's success include spin and placement, but our study did not include those outcome parameters.

4.9 Training recommendations

Training specificity is fundamental for securing optimal adaptation to ensure improved performance and enhanced recovery for the next match.[116] Therefore, understanding the competition demands of tennis is of paramount importance for coaches, strength and conditioning coaches, and tennis players to ensure they plan the appropriate training dose to maximise the fitness-fatigue response within athletes. Goossens et al.[118] studied data from the four Grand Slam Tournaments from 1992 to 2011, covering 20,320 matches. They found that the relative effort invested in winning a match negatively affected the probability of winning the next match. For men, this was the case if they had played two sets more in their previous match than their opponent had, and for women, this was one set.

Tennis players must move well to hit powerful shots with great accuracy while moving sideways, forwards or backward at variable speeds. Players need not only to be fast around the court but also to read the game well and move efficiently around the court [103]. Footwork, anticipation and tactical drills are essential components of the training program for a developing or elite player.

Elite players (e.g., international players) have better physical fitness values and stroke performance levels than sub-elite players (e.g., regional, national, and junior players) [5]. An essential part of the preparation would be to mimic the demands during competition, both in duration, frequency, and intensity, during training. Therefore, it is not enough for a tennis player to be able to run 3 to 5 km at an easy pace. As identified by this review, their running training should include accelerations, decelerations, changes of direction, and high running speeds. Exercises to improve acceleration should be included in the training program. The program may consist of exercises to improve strength, power, agility for direction changes, and speed.

The tennis training and strength and conditioning should mimic the work-to-rest ratios (1:2 to 1:4) experienced in tennis matches. Many tennis drills consist of high volume and continuous loading to acquire skills and develop consistency and economy. However, high-intensity interval exercises with adequate rest periods should be included as well, both on and off court.

The serve and serve-returns are essential strokes in tennis, and youth coaches should prioritise the development of an efficient serve technique and strong serve-returns.[101]

4.9.1 Strengths and limitations

We provide a comprehensive overview of the literature on the physical demands of tennis. A limitation of this review is that some of the studies were conducted over a decade ago, and over time, the rules, match formats, playing surfaces and playing equipment in tennis have changed. We had to rely on the accuracy of collected data, and older data, in particular, may be limited by the quality of the GPS and video tracking. There was also a lack of standardisation in reporting, mainly related to movement variables, making it difficult to compare studies. Most studies focused on international players, with fewer on national or regional players. Most international players were adults, whereas all national-level players were juniors, which made an analysis stratified by age impossible. The relatively low number of studies per outcome variable sometimes precluded meta-analysis or yielded wide confidence and prediction intervals.

It would be interesting to determine whether some outcomes have a time trend. However, we could not study the influence of the covariate/variable "publication year" on different outcome variables (e.g., rally duration). The number of studies is too low (< 10-20) to perform a meaningful random-effects meta-regression.

5 Conclusions

The findings from this systematic review with meta-analysis provide a comprehensive summary of the physical demands of tennis. The results indicate that elite tennis players should have high fitness levels to handle matches of up to three hours or more, followed by a speedy recovery. Players should focus on footwork and movement drills and include many accelerations, decelerations, and changes of directions, with appropriate work-to-rest ratios, rather than straight-line, continuous running. They should prioritise the serve and serve-return. The present study will assist tennis coaches, strength and conditioning trainers and tennis players in better understanding the demands of the game.

5.1 Recommendations for future studies

Due to inconsistent reporting methods, varying cut-off points, and missing standard deviations, we could not include all data in the meta-analysis. We recommend more consistent measuring and reporting of data to enable future meta-analysts to pool meaningful data. Similarly, there is an opportunity for studies to provide access to the individual data sets to allow performing meta-analyses with age as a covariate. Given the wide variability in the data on the distance covered and the lack of sufficient data on peak and average running speed on different surfaces, more studies describing these generalised movement demands are recommended. There is also a need for improved hygiene and standardisation of tracking data in tennis, especially at the professional level. This should include agreement on the treatment or filtering of raw data and expert consensus on measures even as simple as playing time. This work should then extend into the harmonisation or translation of player tracking technologies, where the performances of different systems are compared.

As most data are from professional tennis players, primarily males, more research on athletes at national and regional levels and female players is needed. Unfortunately, the tracking systems used in professional events are not publicly available and remain quite expensive, which precludes their wider use. More affordable computer vision technologies powered by artificial intelligence, and various inertial measurement units look promising in bridging this gap.

Statements and Declarations

Disclosure of potential conflicts of interest

BMP, MGTJ and MvR are employed by the Royal Netherlands Lawn Tennis Association (KNLTB). CB is employed by the Lawn Tennis Association (LTA). SW, SC, KF, NH, DCJvR, VMP, AM, SO, FCLO, MR, TS, LS, JT, NW, and CA declare no conflict of interest.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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Author contributions

Babette Pluim had the idea for the study. Linda Schoonmade conducted the literature search. Tobias Saueressig performed the data analysis. Babette Pluim, Marleen Jansen, Sam Williamson, Christa Janse van Rensburg, Jane Thornton, and Clare Ardern prepared the original draft. All authors critically commented on previous versions of the manuscript and read and approved the final manuscript.

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Table legends:

Table I. Outcome parameters for duration, on-court movement and stroke performance

Table II. (Modified) Joanna Briggs Institute (JBI) checklist score of the studies included in this review (n=64).

Table III. Match duration of international and national male and female players on different court surfaces. *CI* Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *min* minutes, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation.

Table IV. Effective playing time of international and national male and female players on different court surfaces. *CI* Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation.

Table V. Distance covered per match, set, point, and minute of international and national male and female players on different court surfaces. *CI* Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, *NE* Not Estimable, *PI* Prediction Interval, *SD* Standard Deviation.

Table VI. Average and peak running speed of international and national male and female players on hard and clay courts. *CI* Confidence Interval, I^2 I-square statistic, *M* Mean, *MD* Mean Difference, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation.

Table VII. Strokes per rally of international and national male and female players on different court surfaces. *CI* Confidence Interval, I^2 I-square statistic, *M* Mean, *NA* Not Applicable, *PI* Prediction Interval, *SD* Standard Deviation, *#* number.

Table VIII. First and second serve speed of international male and female players on different court surfaces.

Figure legends:

Figure 1. Flow chart of the screening process. *ATP* Association of Tennis Professionals, *ITF* International Tennis Federation, *WTA* Women's Tennis Association.

Figure 2. Mean rally duration (s) of International male tennis players on hard, grass, and clay courts. Dashed lines on the forest plot diamonds represent the 95% prediction interval. *RE* Random Effects.

Figure 3. Mean rally duration (s) of international female tennis players on hard, grass, and clay courts. Dashed lines on the forest plot diamonds represent the 95% prediction interval. *RE* Random Effects.

Figure 4. Mean difference in rally duration (s) between international male and female tennis players on hard, grass, and clay courts. A minus sign signifies a shorter mean rally duration in favour of male players. A plus sign signifies a shorter rally duration in favour of female players. Dashed lines on the forest plot diamonds represent the 95% prediction intervals. *RE* Random Effects.

Figure 5. Summary of the physical demands of tennis in a) international and b) national players.