The Physical Demands of Wheelchair Tennis Match Play: A Systematic Review with Meta-analysis

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SYSTEMATIC REVIEW

The Physical Demands of Wheelchair Tennis Match Play: A Systematic Review with Meta-analysis

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Abstract

Background Wheelchair tennis, a globally popular sport, features a professional tour spanning 40 countries and over 160 tournaments. Despite its widespread appeal, information about the physical demands of wheelchair tennis is scattered across various studies, necessitating a comprehensive systematic review to synthesise available data.

Objective The aim was to provide a detailed synthesis of the physical demands associated with wheelchair tennis, encompassing diverse factors such as court surfaces, performance levels, sport classes, and sexes.

Methods We conducted comprehensive searches in the PubMed, Embase, CINAHL, and SPORTDiscus databases, covering articles from inception to March 1, 2023. Forward and backward citation tracking from the included articles was carried out using Scopus, and we established eligibility criteria following the Population, Exposure, Comparison, Outcome, and Study design (PECOS) framework. Our study focused on wheelchair tennis players participating at regional, national, or international levels, including both juniors and adults, and open and quad players. We analysed singles and doubles matches and considered sex (male, female), sport class (open, quad), and court surface type (hard, clay, grass) as key comparative points. The outcomes of interest encompassed play duration, on-court movement, stroke performance, and physiological match variables. The selected study designs included observational cross-sectional, longitudinal, and intervention studies (baseline data only). We calculated pooled means or mean differences with 95% confidence intervals (CIs) and employed a random-effects meta-analysis with robust variance estimation. We assessed heterogeneity using Cochrane Q and 95% prediction intervals.

Results Our literature search retrieved 643 records, with 24 articles meeting our inclusion criteria. Most available information focused on international male wheelchair tennis players in the open division, primarily competing in singles on hard courts. Key findings (mean [95% CI]) for these players on hard courts were match duration 65.9 min [55.0–78.8], set duration 35.0 min [28.2–43.5], game duration 4.6 min [0.92–23.3], rally duration 6.1 s [3.7–10.2], effective playing time 19.8% [18.9–20.7], and work-to-rest ratio 1:4.1 [1:3.7–1:4.4]. Insufficient data were available to analyse play duration for female players. However, for the available data on hard court matches, the average set duration was 34.8 min [32.5–37.2]. International male players on hard court covered an average distance per match of 3859 m [1917–7768], with mean and peak average forward speeds of 1.06 m/s [0.85–1.32] and 3.55 m/s [2.92–4.31], respectively. These players executed an average of 365.9 [317.2–422.1] strokes per match, 200.6 [134.7–299.0] per set, 25.4 [16.7–38.7] per game, and 3.4 [2.6–4.6] per rally. Insufficient data were available for a meta-analysis of female players' on-court movement and stroke performance. The average and peak heart rates of international male players on hard court were 134.3 [124.2–145.1] and 166.0 [132.7–207.6] beats per minute, and the average match heart rate expressed as a percentage of peak heart rate was 74.7% [46.4–100]. We found no studies concerning regional players or juniors, and only one study on doubles match play.

Conclusions While we present a comprehensive overview of the physical demands of wheelchair tennis, our understanding predominantly centres around international male players competing on hard courts in the open division. To attain a more comprehensive insight into the sport's physical requirements, future research should prioritise the inclusion of data on female and quad players, juniors, doubles, and matches played on clay and grass court surfaces. Such endeavours will facilitate the development of more tailored and effective training programmes for wheelchair tennis players and coaches.

The protocol for this systematic review was registered a priori at the International Platform of Registered Systematic Review and Meta-analysis Protocols (Registration https://doi.org/10.37766/inplasy2023.3.0060).

Key Points

The mean match duration for open class international male and female wheelchair tennis players in singles on hard court was just over an hour.

Mean game duration for male players was around 5 min, with a mean rally duration of 6 s.

Their effective playing time was 20% of the actual playing time, with a work-to-rest ratio of 1:4.

On average, open class international male players covered almost 4 km per match on hard court, with mean and peak average forward speeds of 3.8 and 12.8 km/h.

The average and peak match heart rates of international male players on hard court were 134 and 166 beats per minute, respectively. Average match heart rate expressed as a percentage of peak heart rate was 75%.

These players hit an average of 366 strokes per match, 201 strokes per set, 25 per game, and 3.4 per rally.

1 Introduction

Wheelchair tennis, the Para sport version of tennis [1], caters to individuals with physical impairments and was first played in 1976 [2]. The sport involves playing tennis while seated in a wheelchair and follows the same rules as standing tennis, except that the ball can bounce twice. Matches typically follow a best-of-three-sets format, with tie-breaks used to determine set outcomes when necessary. Wheelchair tennis promotes inclusive participation and psychosocial wellbeing [3], accommodating players at both recreational and professional levels. In recreational play, there is even the flexibility to mix standing and seated players. The sport is played on various court surfaces, including hard courts, clay, and grass.

Wheelchair tennis has two sport classes: the open division, for players with a permanent impairment in one or both of their lower extremities, and the quad division, for players with additional permanent impairments in their upper extremities that limit their ability to handle the racket, play shots, and manoeuvre the wheelchair. Athlete eligibility for participation and class determination is undertaken according to the International Tennis Federation (ITF) classification rules [4]. Current estimates suggest there are around 10,000 recreational wheelchair tennis players globally, with fewer than 1000 participating in regular international competition [5]. The sport is played in over 100 countries, and the ITF wheelchair tennis tour features more than 160 tournaments across 40 countries worldwide [5].

To excel in wheelchair tennis, players must possess various tactical, technical, physical, and psychological skills [6–8]. As the sport evolves, physical attributes have become increasingly important for success at the elite level. The physical demands of wheelchair tennis are extensive, including strength [9], power [10], balance [11], coordination [12, 13], agility [12, 13], and aerobic endurance [14]. The court surface [15, 16], player ranking [17], division [18], age [13], and sex [19, 20] can all influence the demands of match play in wheelchair tennis.

A thorough understanding of the physical demands of wheelchair tennis is central to developing players effectively and monitoring the progression of this relatively new professional sport. While the physical demands of standing tennis have been documented in recent literature [21], there is no published review exploring the physical demands of wheelchair tennis.

Therefore, we aimed to summarise the physical demands of wheelchair tennis, focusing on singles and doubles in the open and quad divisions, across all age groups, sexes, performance levels, and court surfaces, by reviewing the available scientific literature on the subject.

2 Methods

The reporting of this systematic review was guided by the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement [22]. We prospectively registered the review protocol at the International Platform of Registered Systematic Review and Meta-analysis Protocols to ensure transparency and adherence to a predetermined plan (Registrationhttps://doi.org/10.37766/inplasy2023.3.0060).

2.1 Eligibility Criteria

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

The inclusion criteria were:

1. *Population* Male and female wheelchair tennis players of regional, national, or international playing level, including both juniors (≤ 18 years) and adults.
2. *Exposure* Singles and doubles wheelchair tennis matches played on hard court, clay, or grass, following the rules set forth by the ITF.
3. *Comparison* Sex (male/female), court surface (hard, clay, grass), sport class (open/quad).

4. *Outcome* Studies must report 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 speed), stroke performance (count, speed, and scoring), or physiological variables (e.g. heart rate, oxygen uptake [VO_2], energy expenditure, and blood lactate).
5. *Study designs* Descriptive cross-sectional studies, analytic observational prospective and retrospective cohort studies, as well as intervention studies (only baseline data included).

The exclusion criteria were:

1. Editorials, notes, letters, case reports, and reviews
2. Studies of wheelchair tennis with modified match rules (e.g. time-capped matches)
3. Studies of standing (able-bodied) tennis
4. Studies reporting only on biomechanical variables

2.2 Data Sources and Searches

A comprehensive search to identify relevant studies was performed in four bibliographic databases: PubMed, Embase, CINAHL (via EBSCO), and SPORTDiscus (via EBSCO), covering the period from inception to March 1, 2023. The search was developed with a medical information specialist (LJS). It used both controlled search terms (Medical Subject Headings [MeSH] in PubMed, Emtree in Embase, CINAHL Headings in CINAHL, and Thesaurus terms in SPORTDiscus) and free-text terms. The search strategy focused on the keywords ‘wheelchair’ and ‘tennis’ as the index terms or free-text words, along with their synonyms and closely related terms. No language or date restrictions were applied. Duplicate articles were removed by the medical information specialist (LJS) using Endnote X20.5 (Clarivate), following the Amsterdam Efficient Deduplication (AED) method [23] and the Bramer method [24]. A backward citation search was also conducted for all included articles using Scopus. The comprehensive database search strategy can be found in Online Resource 1 (see the electronic supplementary material).

2.3 Selection Process

Two reviewers (SW and BMP) independently screened all titles and abstracts for eligibility using Rayyan [25]. The full-text articles were assessed as required. The inter-rater reliability was assessed using Cohen’s Kappa for both the initial and the final screening. Any discrepancies in the assessment were resolved through discussion until an agreement was reached. If the reviewers could not reach a consensus, an independent reviewer (MGTJ) was available for the final decision. Reasons for exclusion were documented at each stage of the screening process.

2.4 Data Extraction

Two reviewers (SW and BMP) independently extracted the following information regarding the characteristics of the included studies: name of the first author; year of publication; country in which the study was conducted; study design; population; sample size (number of participants and matches); age of participants; percentage of male participants; playing level; court surface; sport class (open or quad); assessment tool(s) used; comparison; and a summary of the outcome parameters of each study. Data related to the outcome were extracted for analysis. When there was overlap between studies, we removed the duplicate data. Authors were contacted if data were missing or required clarification.

The playing level of the participants was determined based on the level of the tournaments the player participated in, such as regional, national, or international, or by their ranking. The sport class (open or quad) was determined by the classification status described in the article or the reported impairment. The court surfaces were classified as hard, clay, or grass, based on the playing surface of the matches. Differences were resolved through discussion, and a third reviewer (MGTJ) was available if consensus could not be reached.

Data related to outcomes in the following areas were extracted (Table 1):

- *Time characteristics* Matches, sets, games, points (rallies), and strokes
- *On-court movement* Accelerations, decelerations, turns, distance covered, and average and peak wheelchair speed
- *Physiological variables* Heart rate, VO_2, energy expenditure, and blood lactate levels
- *Stroke performance* Speed, number, and scoring

2.5 Methodological Quality Assessment

Two reviewers (SW and BMP) used the Joanna Briggs Institute checklist for analytical cross-sectional studies to assess the methodological quality of the included studies [26]. The checklist comprised eight items that included questions on study inclusion criteria, participants, setting, exposure, condition, confounding factors, validity and reliability of the measurement technique, and appropriate statistical analysis. Each question was rated as ‘yes’, ‘no’, or ‘unclear’. Any differences in rating were resolved through discussion until a consensus was reached. The quality assessment outcomes

Table 1 Outcome parameters for time characteristics, on-court movement, stroke performance, and physiological variables

Time characteristics	Stroke performance (speed)
Match/set/game duration (min)	First serve speed (km•h^{-1})
Rally/stroke duration (s), rally pace (strokes•s^{-1})	Second serve speed (km•h^{-1})
Effective playing time (%)	Groundstroke speed (km•h^{-1})
Work-to-rest ratio	Forehand speed (km•h^{-1})
	Backhand speed (km•h^{-1})
On-court movement	
Accelerations/decelerations per min/speed zone/match (n)	**Stroke performance (number)**
Turns per match/min (n)	First serve percentage (%)
Distance covered per match/set/game/point/stroke (m)	Strokes per match/set/game/rally/second (n)
Distance covered per speed zone/min (m)	Serves per match/set/game (n)
Average/peak movement speed (m•s^{-1})	First serves per match/set/game (n)
	Second serves per match/set/game (n)
Physiological match variables	Forehands per match/set/game (n)
Average/peak heart rate (min^{-1}), percentage peak heart rate (%)	Backhands per match/set/game (n)
Oxygen uptake, relative (mL•kg^{-1}•min^{-1})	
Oxygen uptake, absolute (L•min^{-1})	**Scoring**
Percentage peak oxygen uptake (%)	Points per match/set/game (n)
Energy expenditure, relative (kcal/kg/match)	Games per match/set (n), sets per match (n)
Energy expenditure, absolute (kcal/match)	Bounces per point (n)
Mean blood lactate (mmol•L^{-1})	Shots hit off one bounce (%)

were not used to determine study inclusion or for sub-group analysis based on methodological quality or risk of bias.

2.6 Data Synthesis

The analysis examined the outcomes across two broad categories: 'male' and 'female'. Quantitative statistical analysis was conducted by calculating pooled means or mean differences, along with 95% confidence intervals (CIs) for movement variables reported by three or more studies. In cases where median values were provided, the quantile estimation method was employed to estimate the mean and standard deviations [27]. To account for the dependence of study means, a random-effects meta-analysis was performed using robust variance estimation [28, 29]. The inverse variance method was utilised to pool the studies [30]. For analysis, measures of means were log-transformed and subsequently back-transformed to avoid implausible (i.e. negative) estimates [31]. The standard error of the log-transformed mean was calculated using the formula $\sqrt{\frac{SD}{n*\text{mean}}}$ [32].

The Cochrane Q and resulting chi-square statistic, I^2 statistic, and 95% prediction interval were employed to assess the heterogeneity. The 95% prediction interval (PI) estimates where the actual effects are expected to lie for 95% of similar studies that may be conducted in the future. The 95% PI estimate may be imprecise if the number of studies is limited [33]. Therefore, we only provided the 95% PI if we had at least five studies available.

In cases where correlation values were absent, a default correlation value of $\rho = 0.8$ was adopted for all analyses. All calculations and graphical representations were conducted using the software R [34], along with the additional packages 'metafor' [35] and 'robumeta' [36].

Qualitative Synthesis The descriptive characteristics of each study were summarised and presented in tables and text.

Subgroup Analysis The influence of the three main court surfaces used in tennis was considered: hard, grass, and clay.

Analysis of Subgroups or Subsets We planned subgroup analyses with study variables in the following subgroups: male and female; international, national, and regional level players; open and quad division; and juniors and adults.

Sensitivity Analysis As correlation values were unknown, a sensitivity analysis with a range of different correlation parameters was performed ($\rho = 0$, 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 [36]. Sensitivity analyses were calculated without the studies with the imputed standard deviation.

3 Results

3.1 Search

The literature search resulted in 538 references: 85 in PubMed, 116 in Embase, 74 in CINAHL, and 263 in SPORTDiscus. After removing duplicates, 381 papers remained. A forward and backward citation search and handsearching generated an additional 262 references, resulting in a total of 643 records for screening. Based on titles and abstracts, 33 articles that seemed to meet the inclusion criteria were selected. After a full-text screening, nine articles were excluded, leaving 24 articles for the review (Fig. 1). Cohen's Kappa for the initial screening was 0.96 and for the final screening 1.0, indicating a very high level of agreement.

3.2 Characteristics of the Included Studies

Table 2 presents the characteristics of the included articles. All articles were analytical cross-sectional studies. Most of the research originated in Spain [15, 19, 20, 41, 43–51]. The sample sizes of the included papers ranged from four to 64 players, with ten out of 24 studies (42%) having ten participants or fewer. Most papers focused on match data from international players, with three studies specifically examining data obtained from Paralympic athletes [45, 49, 50]. Only two studies included players at the national level [14, 42].

Of the 24 articles, 16 included only male participants [14, 15, 17, 37, 39–41, 43, 44, 46–51, 54], two studies had equal representation of male and female players [19, 20], and one study focused solely on female participants [45]. In the remaining five studies, male players constituted the

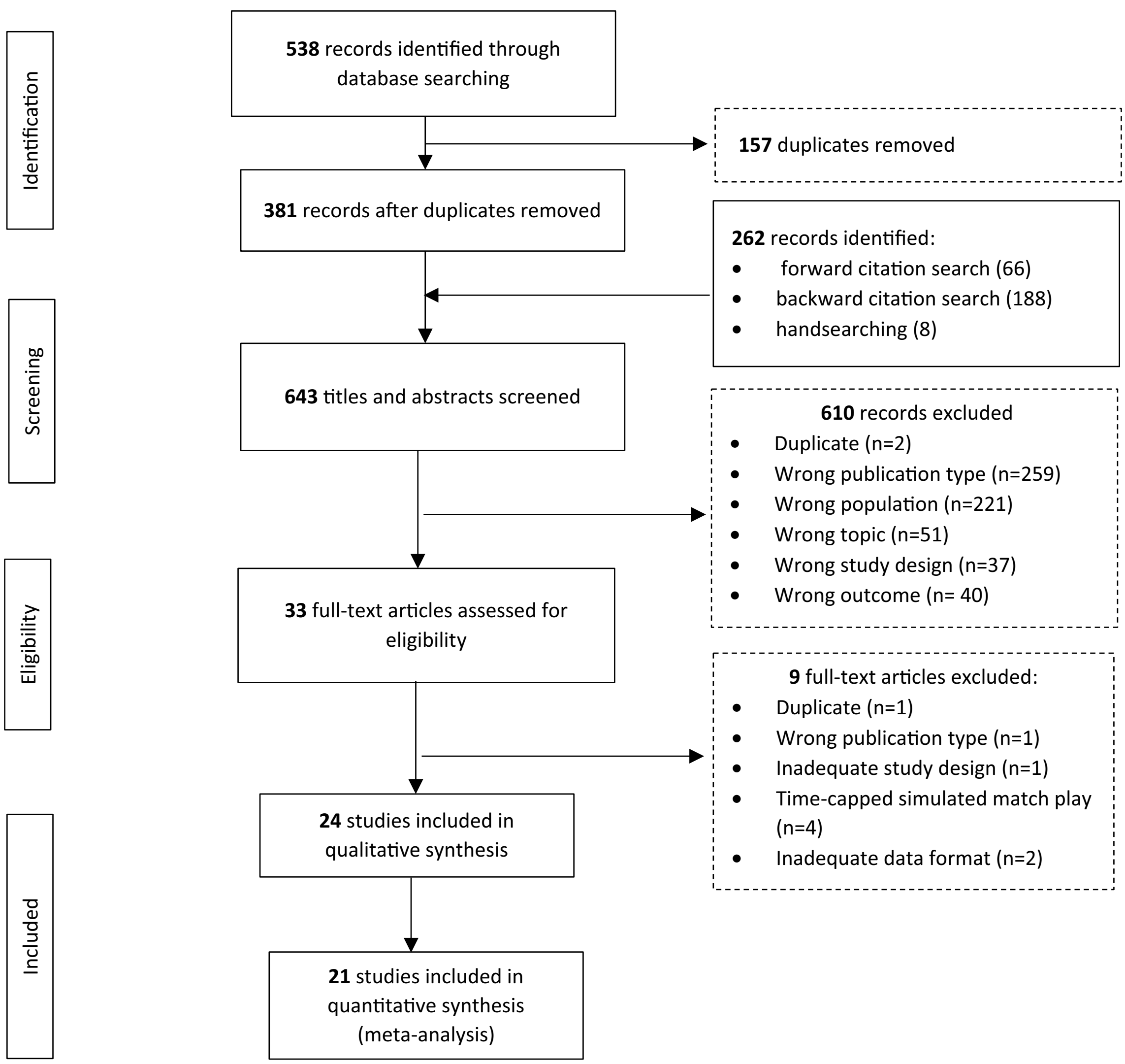

Fig. 1 Flow chart of the screening process

Table 2 Characteristics of the included studies

First author, year, country	Design	Setting	Sample size (*n*)	Matches (*n*)	Age, mean (SD) (y)	Sex: male, *n* (%)	Playing level	Sporting class	Playing surface	Assessment tool	Comparison	Outcomes measures
Bernardi, 2010, Italy [37]	Analytic cross-sectional	Simulated match play (two sets)	4	2	38.5 (10.3)	4 (100)	International	Open	Hard court	HR monitor, incremental arm cranking	Five para sports	Average and peak HR, % peak HR, average VO_2 and $\%VO_{2peak}$
Croft, 2010, UK [38]	Analytic cross-sectional	International tournaments in Florida (USA) and UK	6	6	23 (8.2)	4 (66.7)	International	Open	NR	HR monitor, incremental sub-maximal exercise test	Wheelchair basketball vs wheelchair tennis	Average and peak HR, % peak HR, average VO_2 and $\%VO_{2peak}$
Filipčič, 2009a, Slovenia [39]	Analytic cross-sectional	Simulated match play (two sets)	15	22	39.1 (8.2)	15 (100)	International (5), all minimum 5-y experience	Open	Hard court	Video, SAGIT/TENNIS tracking system	Winner vs losers	Match duration, points per match, rally duration, EPT
Filipčič, 2009b, Slovenia [40]	Analytic cross-sectional	Simulated match play (two sets)	15	22	39.1 (8.2)	15 (100)	International (5/15), minimum 5-y experience	Open	Hard court	Video, SAGIT/TENNIS tracking system	High vs low ranked, winner vs loser	Average and peak forward speed, distance per point/game/match
Gómez, 2021, Spain [41]	Analytic cross-sectional	XXIII Spanish National Masters in Wheelchair Tennis	8	10	39.4 (11.3)	8 (100)	International	Open	Clay court	Video, IMU	High vs low level, high vs high level, low vs low level	Distance per point/match, distance during active play, average forward speed
Mason, 2020, UK [18]	Analytic cross-sectional	NEC Wheelchair Tennis Masters (best of three)	17	22	29 (9), 28 (6), 35 (6)	11 (64.7)	International	Open (7 M, 6 F), quad (4 M)	Hard court	Video, Dartfish TeamPro Data 6.0, IMU, LPS	M vs F, open vs quad	Set duration, distance per set, average and peak forward speed, forward/rotational acceleration, turns per min, strokes per rally, points per set

Table 2 (continued)

First author, year, country	Design	Setting	Sample size (*n*)	Matches (*n*)	Age, mean (SD) (y)	Sex: male, *n* (%)	Playing level	Sporting class	Playing surface	Assessment tool	Comparison	Outcomes measures
Ponzano, 2017, Italy [42]	Analytic cross-sectional	Simulated match play (best of three)	12	12	43.3 (13,3)	10 (83.3)	International (M), national (F)	Open	Hard court, clay	GPS, HR monitor	Hard vs clay court	Match duration, average and peak HR, average and peak forward speed, acceleration, deceleration, kcal per match
Roy, 2006, USA [14]	Analytic cross-sectional	Simulated match play (best of three)	6	6	40.2 (9.8)	6 (100)	International (4), national (2)	Open	Hard court	HR monitor, video	None	Average HR, % peak HR, average VO_2, $\%VO_{2peak}$, kcal per match
Sánchez-Pay, 2013, Spain [43]	Analytic cross-sectional	Roland Garros, US Open (2010, 2011) (best of three)	54	27	NR	54 (100)	International	Open	Clay, hard court	Match statistics	Hard vs clay court	Match duration, first serve percentage
Sánchez-Pay, 2015a, Spain [44]	Analytic cross-sectional	Spanish Wheelchair Tennis Master Cup (two sets)	8	16	NR	8 (100)	International	Open	Hard court	Video	With and without breakpoint opportunity	Match/rally duration, EPT, strokes/points per rally/game/set/match
Sánchez-Pay, 2015b, Spain [19]	Analytic cross-sectional	2014 AO, RG, and US Open (best of three)	96	84	NR	48 (50)	International	Open	Hard court, clay court	Match statistics	Hard vs clay court and wheelchair vs standing tennis	Set duration, points per game/set, first serve percentage
Sánchez-Pay, 2015c, Spain [45]	Analytic cross-sectional	2012 Paralympic Games (best of three)	32	32	NR	0 (0)	International	Open	Hard court	Match statistics	Winners vs losers	First serve percentage

Table 2 (continued)

First author, year, country	Design	Setting	Sample size (n)	Matches (n)	Age, mean (SD) (y)	Sex: male, n (%)	Playing level	Sporting class	Playing surface	Assessment tool	Comparison	Outcomes measures
Sánchez-Pay, 2015d, Spain [46]*	Analytic cross-sectional	Simulated match play (best of three)	4	6	34.8 (11.6)	4 (100)	International	Open	Clay court	Video	None	Rally/set/match duration, WR ratio, points per set/match, strokes per rally/game/set/match, rally pace
Sánchez-Pay, 2016, Spain [47]*	Analytic cross-sectional	Simulated match play (best of three)	4	6	34.8 (11.6)	4 (100)	International	Open	Clay court	HR monitor, lactate analyser, video	Serve vs return situation	Rally/set/match duration, EPT, WR ratio, strokes per rally, average and peak HR, % peak HR, blood lactate
Sánchez-Pay, 2017a, Spain [48]	Analytic cross-sectional	Spanish Wheelchair Tennis Master Cup (best of three)	8	16	NR	8 (100)	International	Open	Hard court	Video	Set winner vs set loser; with vs without game point opportunity	Shots per match
Sánchez-Pay 2017b, Spain [20]	Analytic cross-sectional	International Wheelchair Tennis Tournament (best of three)	16	16	NR	8 (50)	International	Open	Hard court	Video	Male vs female; with vs without game point opportunity	Rally/set/match duration, EPT, WR ratio, strokes/points per set, strokes per rally, rally pace, bounces per point
Sánchez-Pay, 2017c, Spain [49]	Analytic cross-sectional	2012 Paralympic Games (best of three)	64	64	NR	64 (100)	International	Open	Hard court	Match statistics	Set winner vs set loser	First serve percentage

Table 2 (continued)

First author, year, country	Design	Setting	Sample size (n)	Matches (n)	Age, mean (SD) (y)	Sex: male, n (%)	Playing level	Sporting class	Playing surface	Assessment tool	Comparison	Outcomes measures
Sánchez-Pay, 2021a, Spain [50]	Analytic cross-sectional	2004, 2008, 2012, 2016 Paralympic Games (best of three)	NR	12	NR	12 (100)	International	Open	Hard court	Video, LINCE	Paralympic Games in 2004 vs 2008 vs 2012 vs 2016	Game/set/match duration, points per game/set/match, shots per game/set/match
Sánchez-Pay, 2021b, Spain [15]	Analytic cross-sectional	2018 World Cup, Master Cup, Queens Club Championships (best of three)	10	13	31.9 (7.7)	10 (100)	International	Open	Hard court, clay, grass	Video	Hard vs clay vs grass court	Rally/game/set duration, points/shots per game/set, strokes per rally, first serve percentage
Sánchez-Pay, 2023, Spain [51]	Analytic cross-sectional	National Master Cup (best of three)	8	16	38 (10)	8 (100)	International	Open	Clay court	LPS, IMU	Day 1 vs day 2 vs day 3 vs day 4	Distance per match
Sindall, 2013a, UK [52]	Analytic cross-sectional	2010 British Open (three sets)	15	17 (open), 9 (quad)	NR	11 (73.3)	International	Open, quad	Hard court	GPS, data logging device	GPS vs data logger	Distance per match, average and peak forward speed
Sindall 2013b, UK [17]	Analytic cross-sectional	2009 British Open (two sets)	14	14	32.0 (15.4)	14 (100)	International	Open	Hard court	Data logging device, HR monitor	High vs low ranked, winner vs loser	Set/match duration, distance per set/match, average and peak forward speed, average and peak HR, % peak HR
Sindall, 2015, UK [53]	Analytic cross-sectional	Three ITF tournaments (three sets)	31	31	30 (12)	23 (74.2)	International	Open	Hard court	Data logger device, video	High vs low ranked, male vs female, singles vs doubles	Time spent in speed zones

Table 2 (continued)

First author, year, country	Design	Setting	Sample size (*n*)	Matches (*n*)	Age, mean (SD) (y)	Sex: male, *n* (%)	Playing level	Sporting class	Playing surface	Assessment tool	Comparison	Outcomes measures
van der Slikke, 2020, Netherlands [54]	Analytic cross-sectional	2016 NWT Championships 2017 ABN AMRO Open (best of three)	15	15	NR	15 (100)	International	Open	Hard court	Inertial sensors (incl. gyroscope)	Wheelchair basketball vs wheelchair tennis	Average and peak forward speed, peak rotational speed, forward/rotational acceleration

AO Australian Open, *EPT* effective playing time, *F* female, *GPS* global positioning system, *HR* heart rate, *IMU* inertial measurement unit, *ITF* International Tennis Federation, *LPS* local positioning system, *M* male, *min* minute, *NR* not reported, *NWT* National Wheelchair Tennis, *RG* Roland Garros, *UK* United Kingdom, *US* United States, VO_2 oxygen consumption, $\%VO_{2peak}$ percentage of peak oxygen consumption, *WR* work-to-rest ratio, *y* year(s)

*Duplicate data included only once

majority [18, 38, 42, 52, 53]. The open class was more prominently represented than the quad class, with only two studies providing data from quad matches [18, 52].

3.3 Methodological Quality Assessment

Among the 24 studies assessed, fewer than half (11/24; 46%) clearly defined the criteria for inclusion (item 1), and described the participants and setting in detail (item 2). All studies measured the exposure (i.e. tennis match play) validly and reliably (24/24; 100%) (item 3). Just over half of the studies (13/24; 54%) used objective and standard criteria for measuring the condition (i.e. the underlying health condition or physical impairment) (item 4). Three-quarters of the studies adequately identified the confounding variables (18/24; 75%) (item 5), but only 11 out of 24 (46%) stated the strategies used to manage them (item 6). Most studies used valid and reliable outcome measures and appropriate statistical analysis (23/24; 96%) (items 7 and 8) (see Table 3).

3.4 Quantitative Synthesis (Meta-Analysis)

The data are presented as means or mean differences with 95% CIs, and 95% PIs (if available). The datasets used for analysis are available in Online Resource 2, and the meta-analysis results are displayed in Tables IV, V, and VI and Online Resource 3. The main findings are summarised in Fig. 2. Authors Filipčič [40], Sánchez-Pay [15, 20, 50], Sindall [53], van der Slikke [54], van der Slikke (on behalf of Mason) [18], and Tolfrey (on behalf of Croft) [38] responded to our requests to provide missing data or clarification.

3.4.1 Sensitivity Analysis

The sensitivity analysis with varying correlation parameters ($\rho = 0$, 0.2, 0.4, 0.6, 1.0) showed that none of the analyses influenced the results (**Online Resources 4 and 5**).

3.4.2 Time Characteristics

The results of the meta-analysis of the time characteristics are presented in Table 4.

3.4.2.1 Match Duration The average duration of matches played by international male players on hard court was 65.9 min [95% CI 55.0–78.8], with a 95% PI of 41.6–104.4 (Table 4). The average match duration on clay court was 77.7 min [95% CI 49.0–123.0]. The average duration of matches of female players on hard court was 67.7 min [95% CI 13.3–345.6] (two studies). There was not enough information to conduct a meta-analysis for match duration on grass courts for male players, clay or grass courts for female players, or quad players.

3.4.2.2 Set Duration The average set duration of international males in the open division on hard court was 35.0 min with a 95% CI of 28.2–43.5 and a 95% PI of 20.0–61.4, and on clay court, it was 35.8 min with a 95% CI of 29.2–43.8. For female players, the average set duration on hard court was 34.8 min with a 95% CI of 32.5–37.2. There was not enough data to conduct a meta-analysis for set duration for male players on grass courts, female players on clay or grass courts, or quad players.

3.4.2.3 Game Duration The average game duration of international male players in the open division on hard court was 4.6 min [95% CI 0.92–23.3]. There was insufficient information to conduct a meta-analysis for game durations on clay and grass courts, or for female and quad players.

3.4.2.4 Rally Duration The average rally duration of international male players in the open division on hard court was 6.1 s, with a 95% CI of 3.7–10.2. There was insufficient information to conduct a meta-analysis for rally durations on clay and grass courts, or for female and quad players.

3.4.2.5 Effective Playing Time and Work-to-Rest Ratio Effective playing time for international male players on hard court was 19.8% with a 95% CI of 18.9–20.7, and on clay court 17.7% with a 95% CI of 17.5–17.8 (two studies). The work-to-rest ratio was 1:4.1, with a 95% CI of 1:3.7–1:4.4, on hard court and 1:4.1, with a 95% CI of 1:3.6–1:5.6, on clay court (two studies). Insufficient infor-

Table 3 Joanna Briggs Institute (JBI) checklist score (%) of the studies included in this review ($n = 24$)

Author(s) (year)	Item number and corresponding score								Yes	No	Unclear	JBI checklist score
	1	2	3	4	5	6	7	8				
Bernardi et al. (2010) [37]	N	Y	Y	Y	Y	N	Y	Y	6	2	0	6
Croft et al. (2010) [38]	U	Y	Y	Y	Y	Y	Y	Y	7	0	1	7
Filipčič and Filipčič (2009a) [39]	N	Y	Y	Y	N	N	Y	Y	5	3	0	5
Filipčič and Filipčič (2009b) [40]	N	Y	Y	Y	N	N	U	Y	4	3	1	4
Gómez (2021) [41]	Y	N	Y	Y	Y	Y	Y	Y	7	1	0	7
Mason et al. (2020) [18]	N	Y	Y	Y	Y	N	Y	Y	6	2	0	6
Ponzano and Gollin (2017) [42]	N	Y	Y	Y	N	Y	Y	Y	6	2	0	6
Roy et al. (2006) [14]	U	Y	Y	Y	Y	Y	Y	Y	7	0	1	7
Sánchez-Pay et al. (2013) [43]	Y	N	Y	N	N	N	Y	Y	4	4	0	4
Sánchez-Pay et al. (2015a) [44]	Y	N	Y	N	N	N	Y	Y	4	4	0	4
Sánchez-Pay et al. (2015b) [19]	Y	N	Y	N	Y	Y	Y	N	5	3	0	5
Sánchez-Pay et al. (2015c) [45]	Y	N	Y	N	Y	Y	Y	Y	6	2	0	6
Sánchez-Pay et al. (2015d) [46]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	8
Sánchez-Pay et al. (2016) [47]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	8
Sánchez-Pay et al. (2017a) [48]	N	N	Y	N	Y	N	Y	Y	4	4	0	4
Sánchez-Pay et al. (2017b) [20]	Y	N	Y	N	N	N	Y	Y	4	4	0	4
Sánchez-Pay et al. (2017c) [49]	Y	N	Y	N	Y	N	Y	Y	5	3	0	5
Sánchez-Pay and Sanz-Rivas (2021a) [50]	U	N	Y	N	Y	N	Y	Y	4	3	1	4
Sánchez-Pay and Sanz-Rivas (2021b) [15]	Y	N	Y	N	Y	Y	Y	Y	6	2	0	6
Sánchez-Pay et al. (2023) [51]	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	8
Sindall et al. (2013a) [52]	N	N	Y	N	Y	N	Y	Y	4	4	0	4
Sindall et al. (2013b) [17]	N	Y	Y	Y	Y	N	Y	Y	6	2	0	6
Sindall et al. (2015) [53]	N	U	Y	Y	Y	Y	Y	Y	6	1	1	6
van der Slikke et al. (2020) [54]	N	U	Y	U	Y	N	Y	Y	4	2	2	4
Number of studies applying the item	11	11	24	13	18	11	23	23				

Questions from the JBI Checklist: 1. Were the criteria for inclusion in the sample clearly defined? 2. Were the study subjects and the setting described in detail? 3. Was the exposure measured in a valid and reliable way? 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

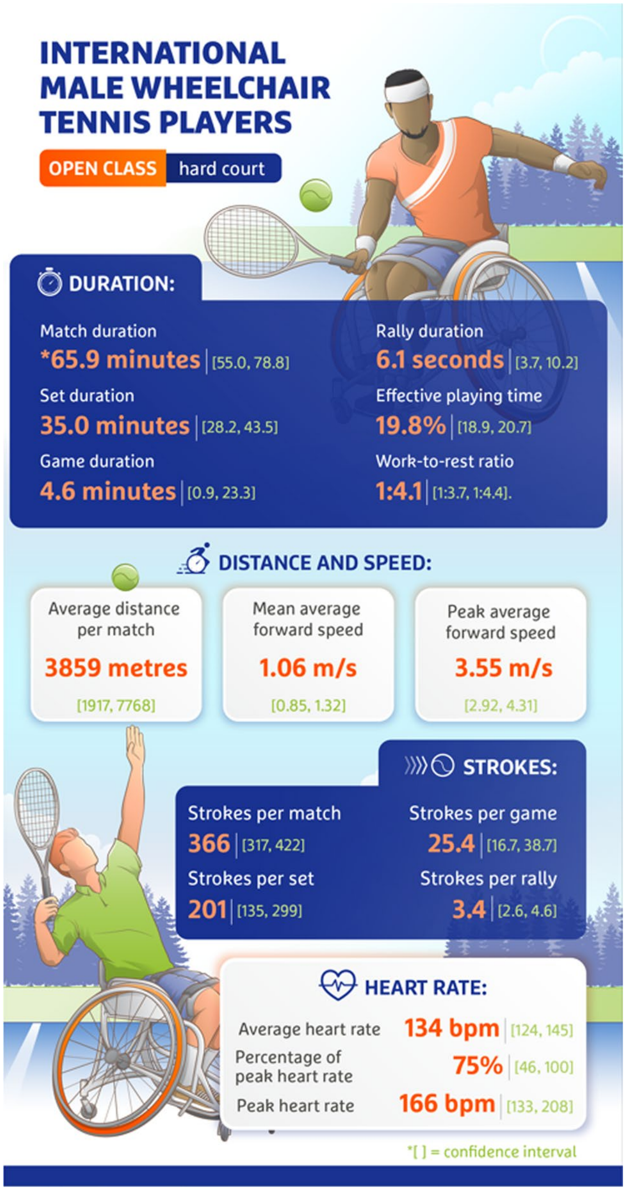

Fig. 2 A summary of the physical demands of wheelchair tennis singles in open class international male players on hard court

mation was available for a meta-analysis of effective playing time of male players on grass court or for female and quad players.

3.4.3 On-Court Movement

The results of the meta-analysis of the on-court movement are presented in Table 5.

3.4.3.1 Accelerations, Decelerations, and Turns Insufficient information was available to conduct a meta-analysis of the number of accelerations, decelerations, and turns during wheelchair tennis matches.

3.4.3.2 Distance Covered The average distance per match covered by international male players in the open division on hard court was 3859 m, with a 95% CI of 1917–7768. Insufficient information was available for a meta-analysis of distance covered per match on clay and grass courts, or for female and quad players.

The average distance covered per set by international males on hard court in the open division was 1900 m, with a 95% CI of 230–15716 (two studies). A meta-analysis was not possible for distance covered per set on clay and grass courts, or for female and quad players, due to insufficient data.

There was also insufficient information for a meta-analysis of distance covered per stroke, point, game, set, or speed zone/min.

3.4.3.3 Movement Speed The average forward speed of international male wheelchair tennis players on hard court was 1.06 m•s^{-1}, with a 95% CI of 0.85–1.32 and a 95% PI of 0.62–1.81. The mean peak forward speed was 3.55 m•s^{-1}, with a 95% CI of 2.92–4.31 and a 95% PI of 2.31–5.45. There was insufficient information to conduct a meta-analysis of the peak and average forward speeds for female and quad players.

3.4.4 Physiological Match Variables

3.4.4.1 Heart Rate The average and peak heart rates of international male players on hard court were 134.3 [124.2–1451.1] and 166.0 [132.7–207.6] beats per minute. Expressed as a percentage of peak heart rate, the average match heart rate was 75%, with a 95% CI of 46.4–100. A meta-analysis was not possible for the average heart rates of male players on clay and grass courts, for female and quad players, and for peak heart rates due to insufficient information.

3.4.4.2 Oxygen Uptake and Energy Expenditure A meta-analysis of VO_2 and energy expenditure of wheelchair tennis players during match play could not be performed due to insufficient data.

3.4.5 Stroke Performance (Speed)

A lack of available information prevented a meta-analysis on the stroke speed of wheelchair tennis players during match play.

3.4.6 Stroke Performance (Number)

The results of the meta-analysis of the stroke performance are presented in Table 6.

Table 4 Time characteristics

Outcome (court type, sex, playing level, division)	Studies included in the meta-analysis (first author, year)	Number of studies	Mean [95% CI]	95% PI	Tau	I^2
Match duration (hard, male, international, open)	Filipčič 2009a [39], Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Mason 2020 [18], Sánchez-Pay 2017b [20], Sánchez-Pay 2015a [44], Sánchez-Pay 2013 [43], Sindall 2013b [17]	8	65.86 min [55.04–78.82]	[41.55–104.42]	0.43	85.78
Match duration (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2016 [47], Sánchez-Pay 2013 [43]	3	77.65 min [49.04–122.96]		0.36	71.09
Match duration (hard, female, international, open)	Mason 2020 [18], Sánchez-Pay 2017b [20]	2	67.66 [13.29–345.64]		0.34	42.62
Set duration (hard, male, international, open)	Mason 2020 [18], Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20], Sánchez-Pay 2015b [19], Sindall 2013b [17]	6	35.04 min [28.21–43.53]	[19.98–61.4]	0.45	86.09
Set duration (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2016 [47], Sánchez-Pay 2015b [19]	3	35.78 min [29.22–43.80]		0.20	26.09
Set duration (hard, female, international, open)	Mason 2020 [18], Sánchez-Pay 2017b [20], Sánchez-Pay 2015b [19]	3	34.79 min [32.54–37.21]		0.21	30.02
Game duration (hard, male, international, open)	Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15]	2	4.63 min [0.92–23.28]		0.41	67.49
Rally duration (hard, male, international, open)	Filipčič 2009a [39], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20], Sánchez-Pay 2015a [44]	4	6.14 s [3.68–10.24]		0.57	99.83
Effective playing time (%) (hard, male, international, open)	Filipčič 2009a [39], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20], Sánchez-Pay 2015a [44]	4	19.81% [18.93–20.74]		0.00	0.00
Effective playing time (%) (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2016 [47]	2	17.65% [17.54–17.76]		0.00	0.00
Work rest ratio (hard, male, international, open)	Sánchez-Pay 2015a [44], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20]	3	1:4.05 [1:3.71–1:4.41]		0.00	0.00

CI confidence interval, I^2 *I*-square statistic, *min* minute(s), *PI* prediction interval, *s* seconds, *Tau* Kendal's Tau

3.4.6.1 First Serve Percentage The percentage of accurate first serves for international male players on hard court was 64.6%, with a 95% CI of 57.8–72.2. It was 66.3% on clay court, with a 95% CI of 61.3–71.6. For female players on hard court, the average percentage of first serves was 59.3%, with a 95% CI of 57.9–60.7.

3.4.6.2 Strokes per Match, Set, Game, and Rally The average number of strokes per match of international male players on hard court was 365.9, with a 95% CI of 317.2–422.1, and on clay court, it was 405.0, with a 95% CI of 24.5–6691.3. The average number of strokes per set on hard court was 200.6, with a 95% CI of 134.7–299.0; per game, it was 25.4, with a 95% CI of 16.7–38.7; and per rally, it was 3.4, with a 95% CI of 2.6–4.6. For female players, the average number of strokes per rally was 3.1, with a 95% CI of 3.1–3.1.

There was insufficient information available to conduct a meta-analysis for the average number of strokes per rally, game, and set on clay and grass courts, as well as for female and quad players.

3.4.7 Scoring

3.4.7.1 Points per Match, Set, and Game The average number of points per match for international male players on hard court was 126.2, with a 95% CI of 93.2–170.9. Their

Table 5 On-court movement

Outcome (court type, sex, playing level, division)	Studies included in the meta-analysis	Number of studies	Mean [95% CI]	95% PI	Tau	I^2
Distance per match (hard, male, international, open)	Mason 2020 [18], Sindall 2013a [52], Sindall 2013b [17]	3	3859.22 m [1917.19–7768.45]		0.34	42.62
Distance per set (hard, male, international, open)	Mason 2020 [18], Sindall 2013b [17]	2	1900.48 m [229.82–15,715.86]		0.47	82.46
Average forward speed (hard, male, international, open)	Filipčič 2009b [40], Mason 2020 [18], Sindall 2013a [52], Sindall 2013b [17], van der Slikke 2020 [54]	5	1.06 m•s^{-1} [0.85–1.32]	[0.62–1.81]	0.42	96.49
Peak forward speed (hard, male, international, open)	Filipčič 2009b [40], Mason 2020 [18], Sindall 2013a [52], Sindall 2013b [17], van der Slikke 2020 [54]	5	3.55 m•s^{-1} [2.92–4.31]	[2.31–5.45]	0.37	95.75

CI confidence interval, I^2 *I*-square statistic, *PI* prediction interval, *Tau* Kendal's Tau

average number of points per set on hard court was 58.0, with a 95% CI of 51.7–65.0, and on clay court, it was 58.9, with a 95% CI of 42.9–80.8. Their average number of points per game on hard court was 6.6, with a 95% CI of 6.3–6.9, and on clay court, it was 7.1, with a 95% CI of 5.0–9.9.

For international female players on hard court, the average number of points per set was 57.6, with a 95% CI of 52.0–63.9.

There was insufficient information for a meta-analysis of the average number of points per game, set, and match on all surfaces for female and quad players, except for the number of points per set for females on hard court. Moreover, there was insufficient information for meta-analysis of the number of games per match and set, and for the number of sets per match.

3.5 Qualitative (Descriptive) Synthesis

Several outcome parameters, such as rotational speed, turns per minute, accelerations, decelerations, heart rate, VO_2, energy expenditure, and blood lactate, had to be excluded from the meta-analysis due to a lack of data. The primary findings are outlined below (for additional details, please refer to Online Resource 2). Additionally, results from studies directly comparing open class men, women, and quads in a single study, or those examining court surface variations, could not undergo meta-analysis due to insufficient available data, and are presented separately below.

3.5.1 Time Characteristics

3.5.1.1 Rally, Set, and Match Duration Sánchez-Pay et al. [20] compared the rally, set, and match durations of eight male and eight female wheelchair tennis players in an international hard court tournament in the open division. The average match duration, expressed as mean (standard deviation), was 64.7 (13.4) min for males and 77.6 (31.7) min for females. The mean set duration was 30.4 (8.0) min for males and 34.5 (9.1) min for females. These differences were not statistically significant. There was a statistically significant difference in rally duration between male and female players, with an average rally duration of 5.58 s (3.65) in male players and 6.82 s (4.83) in female players ($p = 0.001$).

Mason et al. [18] compared set duration between open male and female players, and quad players during the 2017 NEC Wheelchair Tennis Masters on hard court. The study included the best internationally ranked players: seven male players who played 21 sets, six female players who played 17 sets, and four quad players who played 11 sets. Set duration in male players was 39 min:18 s (12:22), in female players, it was 34:01 (10:43), and in quad players, it was 28:50 (08:07), showing statistically significant differences between open male versus quad, and open female versus quad.

3.5.1.2 Rally Pace Sánchez-Pay et al. [20] compared rally pace between male and female matches on hard court. Male players averaged a rally pace of one stroke every 1.9 (0.38) s, while female players averaged one stroke every 2.15 (0.41) s [20]. In another study, Sánchez-Pay et al. [46] measured rally pace in four male players on clay court, and found that they averaged one stroke every 2.2 s.

3.5.1.3 Effective Playing Time and Work-to-Rest Ratio Sánchez-Pay et al. [20] compared effective playing time and work-to-rest ratio in male and female players on hard court. They reported an effective playing time of 20.8% (3.4) in male players and 22.3% (5.2) in female players. For the work-to-rest ratio, the numbers were 1:3.95 (1:0.86) in

Table 6 Stroke performance (number) and scoring

Outcome (court type, sex, playing level, division)	Studies included in the meta-analysis (first author, year)	Number of Studies	Mean [95% CI]	95% PI	Tau	I^2
First serve percentage (hard, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2015b [19], Sánchez-Pay 2013 [43], Sánchez-Pay 2017c [49]	4	64.56% [57.77–72.15]		0.12	5.80
First serve percentage (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2015b [19], Sánchez-Pay 2013 [43]	3	66.28% [61.34–71.61]		0.00	0.00
First serve percentage (hard, female, international, open)	Sánchez-Pay 2015b [19], Sánchez-Pay 2015c [45]	2	59.3% [57.90–60.72]		0.18	35.77
Strokes per match (hard, male, international, open)	Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2017a [48], Sánchez-Pay 2015a [44]	4	365.91 [317.21–422.07]		0.00	0.00
Strokes per match (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2015d [46]	2	405.01 [24.51–6691.3]		0.54	86.65
Strokes per set (hard, male, international, open)	Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20], Sánchez-Pay 2015a [44]	4	200.64 [134.65–298.97]		0.46	89.33
Strokes per game (hard, male, international, open)	Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2015a [44]	3	25.4 [16.68–38.68]		0.45	93.74
Strokes per rally (hard, male, international, open)	Mason 2020 [18], Sánchez-Pay 2015a [44], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20]	4	3.43 [2.56–4.60]		0.32	98.54
Strokes per rally (hard, female, international, open)	Mason 2020 [18], Sánchez-Pay 2017b [20]	2	3.10 [3.10–3.10]		0.00	0.00
Points per match (hard, male, international, open)	Filipčič 2009a [39], Sánchez-Pay 2021a [50], Sánchez-Pay 2015a [44], Sánchez-Pay 2021b [15]	4	126.19, [93.2–170.85]		0.44	85.94
Points per set (hard, male, international, open)	Mason 2020 [18], Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2017b [20], Sánchez-Pay 2015a [44], Sánchez-Pay 2015b [19]	6	57.95 [51.66–65.01]	[45.36–74.05]	0.29	60.38
Points per set (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2015b [19], Sánchez-Pay 2015d [46]	3	58.85 [42.87–80.79]		0.33	71.77
Points per set (hard, female, international, open)	Mason 2020 [18], Sánchez-Pay 2015b [19], Sánchez-Pay 2017b [20]	3	57.64 [52.02–63.86]		0.00	0.00
Points per game (hard, male, international, open)	Sánchez-Pay 2021a [50], Sánchez-Pay 2021b [15], Sánchez-Pay 2015a [44], Sánchez-Pay 2015b [19]	4	6.56 [6.26–6.87]		0.29	90.48
Points per game (clay, male, international, open)	Sánchez-Pay 2021b [15], Sánchez-Pay 2015b [19], Sánchez-Pay 2015d [46]	3	7.07 [5.04–9.93]		0.24	67.68

CI confidence interval, I^2 *I*-square statistic, *PI* prediction interval, *Tau* Kendal's Tau

male players and 1:3.72 (1:1.11) in female players. There were no data on effective playing time and work-to-rest ratio in quad players.

3.5.2 On-Court Movement

3.5.2.1 Accelerations and Decelerations Two studies examined acceleration in wheelchair tennis. Mason et al. [18] investigated average forward and rotational acceleration on hard courts in international male and female open class and quad players. The mean forward acceleration, measured in m•s^{-2}, was 1.08 (0.18) for male players, 0.91 (0.15) for female players, and 0.72 (0.08) for quad players. Similarly, the mean rotational acceleration, measured in deg•s^{-2}, was 205 (28) for male players, 211 (29) for female players, and 144 (31) for quad players. The differences between the open division and the quad division were statistically significant ($p < 0.0005$).

In the study by Ponzano and Gollin [42], the mean maximum acceleration and deceleration were compared on clay and hard courts. They studied a group consisting of ten male and two female wheelchair tennis players. The mean maximum acceleration on clay and hard courts was 1.5 (0.2) m•s^{-2}. The mean maximum deceleration in the same group of players was – 1.68 (0.27) m•s^{-2} on clay court and – 1.63 (0.32) m•s^{-2} on hard court.

3.5.2.2 Turns In wheelchair tennis, turns serve the same purpose as direction changes in standing tennis. The study conducted by Mason et al. [18] examined the frequency of turns per minute and categorised them into turns towards the racket hand and turns towards the non-racket hand. The results showed that male players had an average of 5.6 (0.5) turns towards the racket hand, while female players had 6.2 (1.1) turns per minute. Quad players averaged 4.9 (0.8) turns per minute towards the racket hand. Similarly, the number of turns per minute towards the non-racket hand was 7.5 (0.7) for male players, 7.2 (1.0) for female players, and 6.8 (0.6) for quad players. The differences between the open division and the quad division were statistically significant ($p < 0.0005$ for turns to the racket hand and $p = 0.016$ for turns to the non-racket hand).

3.5.2.3 Distance Covered During a Set Mason et al. [18] used an indoor tracking system and inertial measurement units to measure the distance covered during an average set of open class male and female players and quads on hard court. This system has been investigated previously and been shown to provide valid and reliable data [56]. They found that male players covered the longest distance (2220 m), followed by female players (1840 m), with quad players covering the shortest distance (1275 m).

Sindall et al. [17] measured the distance covered per match on hard court by international male tennis players in the open and quad class by comparing the use of a general positioning system (GPS) and a data logging device. Distance covered by open class players measured by GPS was 2891 (1000) m versus 3963 (1340) m measured by a data logging device. This difference was statistically significant ($p = 0.0001$). In quad players, these numbers were 2675 (438) m and 3931 (505) m, respectively ($p = 0.0001$).

Filipčič and Filipčič [40] reported on distance covered per point, game, and match by 15 male players who played 22 singles matches on hard court, using video analysis with the SAGIT/TENNIS tracking system. They found a distance of 6.1 (2.0) m per point (rally), 26.2 (26.9) m per game, and 613.0 (273.2) m per match. It should be noted that they only measured distance covered during the active phase of play. Gómez [41] measured the distance per point and per match of eight international male tennis players in the open division during ten matches on clay court, and compared the distance covered during the active phase of the match and during the total match. Distance per point was 7.8 (8.4) m, distance during active play was 633.7 (266.8) m, and during the whole match, it was 3372.8 m.

No studies reported on distance per game or per point (rally) in female or quad players.

3.5.2.4 Movement Speed Sindall et al. [17] compared forward movement speed using GPS and a data logging device in open and quad class players on hard court. The average and peak speed of open class players using GPS was 0.8 (0.1) m•s^{-1} and 3.5 (0.4 m•s^{-1}, and 1.0 (0.2) and 3.3 (0.6) m•s^{-1} using data logging. In quad players, these numbers were 0.6 (0.1) and 3.1 (0.2) m•s^{-1} for GPS and 0.9 (0.0) and 2.8 (0.4) m•s^{-1} for data logging.

Van der Slikke et al. [54] measured average and peak rotational speed in international male wheelchair tennis players on hard court (open class). They recorded a mean peak rotational speed of 369 (79) deg•s^{-1}. They did not measure female or quad players.

3.5.3 Physiological Match Variables

3.5.3.1 Heart Rate Sindall et al. [17] measured a peak heart rate of 167 (22) beats per minute in 12 male players on hard court. Sánchez-Pay et al. [47] studied four male players on clay court during simulated match play, and their average and peak heart rates were 124.3 (24.7) and 163.3 (11.6) beats per minute. Croft et al. [38] reported an average and peak heart rate of 146 (16) and 180 (18) beats per minute in four males and two females on hard court. Ponzano and Gollin [42] compared average and peak heart rate on clay and hard court in a group of ten males and two females. Average and peak heart rates on hard court were 123.0 (14.0) and 159.0 (16.0), and on clay court, they were 123.3 (18.4) and 158.6 (18.4) beats per minute.

3.5.3.2 Oxygen Uptake Three studies examined VO_2 in wheelchair tennis. Bernardi et al. [37] calculated average VO_2 in four male paralympic wheelchair tennis players during two tennis matches. This calculation was based on their peak VO_2 achieved during an incremental arm cranking exercise and heart rate monitoring during simulated match play. The average VO_2 during play was recorded as 24.2 (2.6) mL•kg^{-1}•min^{-1} and 1.7 (0.18) L•min^{-1}, equivalent to 73% of their peak VO_2.

Croft et al. [38] investigated the peak VO_2 in four male and two female international wheelchair tennis players on a hard court. The players performed submaximal and VO_2 peak tests in their sport-specific wheelchairs on the treadmill. Heart rate was monitored during competition, and the researchers calculated the average and peak VO_2 during play using linear regression equations. The average VO_2 was determined to be 1.36 (0.42) L•min^{-1}, equalling 68% of their peak VO_2.

In a study conducted by Roy et al. [14], the average VO_2 of six skilled wheelchair tennis players was calculated. This estimation was based on their VO_2 levels during an arm crank ergometer test and heart rate monitoring during simulated match play. Each player participated in two matches on hard court. The average estimated VO_2 during match play was 27.1 $mL•kg^{-1}•min^{-1}$, equalling 49.9% of the peak VO_2 achieved during the ergometer test.

3.5.3.3 Energy Expenditure Two studies investigated energy expenditure during a wheelchair tennis match. Ponzano and Gollin [42] compared the energy expenditure of ten male and two female tennis players on clay and hard courts. Energy expenditure was 3.7 (0.9) $kcal•kg^{-1}$ per match on clay courts and 3.3 (0.8) $kcal•kg^{-1}$ per match on hard courts. This corresponds to approximately 238 (68) and 217 (78) kcal per match.

Roy et al. [14] studied the physiological responses of six skilled male wheelchair tennis players during two tennis matches on hard court. The participants completed an arm crank ergometer test that measured heart rate via a telemetry device and VO_2 peak via open circuit spirometry. He estimated their energy expenditure based on their heart rate during the match and found a mean value of 365 kcal per match.

3.5.3.4 Blood Lactate Levels Sánchez-Pay et al. [47] studied blood lactate levels during simulated match play of four wheelchair tennis players (three matches each). Capillary blood was extracted from the earlobe during the changeovers after each of the unequal number of games, i.e. 1st, 3rd, and 5th game and so on, until the end of each match. The mean blood lactate concentration was 1.41 $mmol•L^{-1}$ (0.43), based on 55 samples.

3.5.4 Stroke Performance (Number)

3.5.4.1 Strokes per Rally Two studies compared the number of strokes in different player groups. Sánchez-Pay et al. [20] compared the number of strokes per rally between male and female players on hard court. They found that male players had an average of 3.9 (1.7) strokes per rally, and female players had an average of 3.1 (2.0) strokes per rally. Mason et al. [18] also investigated this aspect and reported that male players had an average of 3.1 (0.5) strokes per rally, while female players had a similar average of 3.1 (0.8) strokes per rally. For quad players, the average was 2.5 (0.5) strokes per rally.

3.5.4.2 Strokes per Set Sánchez-Pay et al. [20] compared the number of strokes per set between male and female players, and found an average of 157.2 (31.1) strokes per set for male players and 180.5 (77.8) for female players.

Sánchez-Pay and Sanz-Rivas [15] compared the number of strokes per set for male players on different court surfaces. The study found that male players had an average of 272.9 (92.1) strokes per set on hard court, 206.0 (28.6) on clay court, and 184.2 (47.1) on grass court.

3.5.5 Scoring

3.5.5.1 Games per Set Sánchez-Pay et al. [20] presented findings on the average number of games per set played by male and female international wheelchair tennis players during the 2014 Australian Open (hard court), Roland Garros (clay court), and US Open tournaments (hard court). The results indicated that male players averaged 8.8 (2.4) games per set at the Australian Open, 8.9 (2.1) at Roland Garros, and 9.8 (2.4) at the US Open. Female players averaged 8.3 (1.3) games per set at the Australian Open, 8.1 (1.1) at Roland Garros, and 9.6 (2.2) at the US Open.

3.5.5.2 Bounces per Point In this same study, conducted by Sánchez-Pay et al. [20], the researchers also examined the number of bounces per point. The average number of bounces per point was reported as 2.46 (1.85) for male players and 2.97 (2.53) for female players.

3.5.5.3 Shots Off One Bounce Mason et al. [18] studied the percentage of shots played off a single bounce. Their results revealed that male players hit 85.7% (6.8) of their shots after a single bounce, while female players hit 82.1% (7.6) off one bounce. Similarly, quad players hit 81.5% (6.2) after one bounce.

Sánchez-Pay and Sanz-Rivas [15] studied the percentage of shots played after one, two, or no bounce on different court surfaces. There was a statistically significant difference between court surfaces for shots played without bounce, with higher values on grass court (4.6%) than on hard (3.0%) or clay court (2.2%). No statistically significant differences were found between court surfaces for shots played after one or two bounces.

4 Discussion

This systematic review aimed to assess the physical demands of open and quad class male and female wheelchair tennis players, playing on various surfaces, by analysing existing literature and examining key factors such as play duration, on-court movement, stroke performance, and physiological variables during matches. We provide insights into the duration of matches, sets, and rallies, effective playing time, and work-to-rest ratio. We describe stroke performance, including the first-serve percentage, and on-court wheelchair movement, including distance covered, forward speed, accelerations, decelerations, and turns. Finally, we consider physiological variables like heart rate, VO_2, and energy expenditure during matches. The compiled data can guide players, coaches, and support staff when customising training programmes and devising effective match strategies. Our analysis provides a baseline of knowledge for future work as more data becomes available on different court surfaces.

4.1 Time Characteristics

Matches in wheelchair tennis, particularly for international male players in the open class on hard court, were generally shorter (approximately 65 min) than matches in standing tennis (approximately 90 min) [21]. The opponents' skill and competition depth play a crucial role in match duration. Evenly matched players are more likely to engage in extended points, games, and sets, resulting in longer matches. At the moment, wheelchair tennis does not possess the same level of competition depth as standing tennis, and matches are shorter, particularly in the early rounds of a tournament.

However, given that only nine studies analysed the duration of wheelchair tennis matches, as well as the variety of playing conditions (indoor vs outdoor, official vs simulated, two sets plus super tie-break vs best of three sets, court pace or type of ball among others), it is difficult to draw more detailed conclusions. There was a lack of research focusing on female players, quad players, juniors, and lower-level players, which limits a comprehensive understanding of match duration across different categories.

On average, male and female wheelchair tennis players had similar set duration, around 35 min. These durations were generally shorter than those typically seen in Association of Tennis Professionals (ATP) and Women's Tennis Association (WTA) players during Grand Slam events [19]. Variability in set duration seemed to be a function of the number of games per set, a relationship that has also been observed in standing tennis [21].

Wheelchair tennis players had a slower pace of play than standing tennis players. Despite having slightly longer rally durations, the number of strokes per rally was lower in wheelchair tennis, pointing to an overall slower pace of the game. Mason et al. [18] found that male wheelchair tennis players hit 86% of their shots after the first bounce, in contrast with 82% by female and quad players. Most winners were hit after one bounce (91%, 92%, and 88%, respectively), indicating that the second bounce is primarily used in defensive situations. This finding seems to contrast with a prior study that found more frequent and arguably tactical use of the second bounce by higher-ranked players compared to their lower-ranked counterparts [57]. Further dissecting the strategic interplay between ball bounce and other game context such as the players' court position, use of forehand/backhand, and the trajectory of the shots, which are currently missing from the literature, will provide even more practical insight to interpret rally dynamics. Regardless, it is interesting that the effective playing time was similar in wheelchair and standing tennis, hovering around 20%. Nonetheless, the shorter rally duration, the slower rally pace as well as the use of the second bounce show that wheelchair tennis is tactically different from standing tennis, so it is important to design training programmes specifically for this sport.

Comparing the time and game characteristics regarding playing surface in several studies showed relatively small differences between both sexes [15, 19, 43].

4.2 Stroke Performance

At the Grand Slams, the first-serve percentages (the proportion of accurate first serves) of wheelchair tennis players were similar to standing tennis players [19]. However, the percentage of points won on first serves was approximately 10–15% lower in wheelchair tennis players. Serve speed and placement of the ball are important factors that determine the success rate of the stroke. The lower success rate of first serves in wheelchair tennis can be attributed to three primary factors. Firstly, wheelchair tennis players have a lower hitting plane compared to standing players [58, 59], meaning their serves cannot feature the same horizontal velocity profile. Secondly, wheelchair tennis players generate less force due to the absence of leg drive, resulting in lower serve speed [60]. Thirdly, wheelchair tennis players serve in a static position, making it difficult to overcome the inertia to move and hit the next ball from an optimal position [61].

Regrettably, there was limited additional information regarding stroke performance in wheelchair tennis, including metrics such as stroke speed and the frequency of different stroke types, and further studies are eagerly anticipated.

4.3 On-Court Movement

On-court movement plays a pivotal role in wheelchair tennis, and this review showed some interesting findings. Within the open division, male players covered the most ground per set, followed by their female counterparts, while quads covered the shortest distance [18]. This discrepancy in distance covered can be attributed, at least in part, to the greater forward acceleration and speed observed in male players within the open division. These differences may be influenced by the inherent upper body strength advantage of male open class players compared to females and quad players, who, by definition, have at least one upper limb affected, which may well impact their ability to manoeuvre the chair.

The extent of ground covered is related to the match's scoring dynamics. A closely contested match often leads to more and longer points, contributing to an overall increase in the distance covered by the players on the court.

Average speed and maximum speed, acceleration, and deceleration did not differ between hard and clay court in a study with 12 nationally ranked male tennis players and a counterbalanced design [42]. Playing surface did not affect the players' performance. Further studies, including on grass, are needed.

It is also important to consider the measurement methods employed in the study. Filipčič and Filipčič [40] reported the lowest distance covered during a tennis match, which was 613 m, using video analysis with the SAGIT/TENNIS tracking software. These lower values can be attributed to the researchers' decision to solely consider movement during points played, unlike other studies [17, 51, 52] that encompassed the entirety of the match.

This hypothesis gains support from research by Gómez [41], who examined ten matches from the XXIII national male wheelchair tennis masters in Spain. Gómez compared the distance covered during the active phase of play to the total match time, using wireless inertial movement units (WIMU PRO™, RealTRack Systems, Spain). The distance covered during the active phase of play measured 634 m, while during the total match time, it extended to 3373 m.

Sindall et al. [52] compared the criterion validity and accuracy of 1 Hz GPS and a data logging device attached to the wheels. GPS values for distance and speed were consistently lower than equivalent values obtained by data logging. GPS with higher sampling rates than 1 Hz were recommended by the authors for wheelchair tennis, because the measurement device used should be valid and reliable.

There is room to more comprehensively examine the movement demands of wheelchair tennis. Validated technologies and standardisation of measurement are critical in this regard, and the increased use of optical tracking systems in Grand Slam tennis holds considerable promise to further develop an understanding of the sport.

4.4 Physiological Variables

The studies conducted [14, 37, 38, 42, 47] reported an average heart rate ranging from 121 to 146 beats per minute, with peak heart rates spanning 158–180 beats per minute. The average match heart rate expressed as a percentage of peak heart rate ranged from 66 to 78%. Heart rate monitoring offers a means to infer the intensity of play, monitor training programmes, and design effective training programmes. However, while heart rate monitoring serves as a valuable tool to assess play intensity, there are a range of additional factors that can influence heart rate among wheelchair tennis players. These factors encompass age (with lower heart rates in older individuals) [62], the level of spinal cord injury (with lower heart rates in cases of higher spinal cord injury) [63], training level (linked to lower heart rates in individuals that are better trained) [64], and the extent of body muscle mass used (tied to lower heart rates when less body muscle mass is involved) [65].

Ponzano and Gollin [42] compared mean and peak heart rates as well as energy expenditure of 12 nationally ranked wheelchair tennis players on clay and hard courts, and found closely matched values on both playing surfaces. The estimated energy expenditure figures (approximately 220 kcal per match on hard court and 240 kcal on clay) were slightly lower than those reported by Roy et al. [14] for six competitive wheelchair tennis players on hard courts (350 kcal). Notably, Ponzano and Gollin derived their energy expenditure calculations based on GPS data and metabolic power, while Roy et al. based their estimations on VO_2 during an arm ergometer test and heart rate recordings during match play. These different methodological approaches complicate the direct comparison of findings between the two studies.

4.5 Comparison to Other Sports

Elite male wheelchair padel players covered shorter distances per set (around 320 m) than elite male wheelchair tennis players (around 1900 m) [66]. Wheelchair padel players also moved slower (around 0.54 m/s versus 1.1 m/s), and displayed a lower percentage of peak heart rate (65–68%) than wheelchair tennis players (75%), indicating a lower intensity of play in wheelchair padel. When comparing the activity demands of wheelchair tennis to wheelchair basketball, a systematic review showed that basketball players covered longer distances (5–6 km vs 4 km) in shorter time periods (40 vs 65 min) at a higher percentage of peak heart rate (85% vs 75%), indicating that wheelchair basketball is played at a higher intensity than wheelchair tennis [67]. In a comparative analysis of wheelchair mobility performance among wheelchair basketball, tennis, and rugby players in a single study, the results indicated that wheelchair basketball players showed the highest average wheelchair mobility performance levels, while rugby displayed the lowest. Wheelchair tennis fell between the two sports for most outcomes [54].

4.6 Training Recommendations

The compiled data can serve as a valuable resource for players and coaches in customising training programmes and devising effective match strategies. Indeed, quantifying the demands of the game often represents an important initial step in best actioning the principles of specificity and overload in training settings. In a practical sense, by synthesising representative internal load such as expected heart rates in wheelchair tennis, off-court training can be shaped more specifically and so too can exercise testing [68]. Monitoring heart rate provides crucial insights into the player's response to training load and helps assess fatigue levels, aiding in early injury prevention and detection [69]. During practice, players should be able to easily cover a distance of at least 4 km in intervals. For individuals with a spinal cord injury below T5, it is recommended to strive to regularly achieve an intensity of at least 75% of peak heart rate. For those with a spinal cord lesion above T5, a preferred method of intensity monitoring would be rate of perceived exertion (RPE), and players should be able to maintain an intensity of 8/10.

Statistics related to match duration, on-court movement, and stroke performance are also valuable for simulating match play during training sessions and formulating effective tactics during tournaments. Training programmes should prioritise maximising cardiovascular fitness, building strength, and incorporating wheelchair manoeuvring drills. Players should also commit training time to developing skills like quick turns and improving stroke efficiency, particularly in serving. Markers of external load like stroke count can provide an important guide for trunk and upper limb conditioning. With technological advance, it is likely that these markers will become more joint or limb specific in the future to further aid player preparation. By combining physiological data and performance statistics, players can tailor their physical, technical, tactical, and mental programmes to excel in wheelchair tennis.

4.7 Strengths and Limitations

We thoroughly reviewed the existing literature regarding the physical demands of wheelchair tennis. One notable limitation is the scarcity of studies investigating the physical demands on clay and grass courts. Similarly, there is a lack of research focusing on female players, quad players, lower-level players, juniors, and doubles play.

Most existing studies have concentrated on the physical demands of international male wheelchair tennis players participating in the open class, specifically on hard courts. The limited number of studies available for each specific outcome variable often hindered the possibility of conducting meta-analyses, and resulted in wide CIs and PIs. Additionally, we have concerns about the reliability and validity of certain measurement techniques used for on-court movement analysis within the included studies. This may impact the accuracy of the data collected and, in turn, influence the reliability of our conclusions relating to on-court movement.

5 Conclusion

Our understanding of the physical demands of wheelchair tennis is largely centred around international male players on hard courts in the open division. To provide a truly comprehensive understanding of the sport's physical requirements, future research should prioritise the inclusion of data on female and quad players, and matches played on clay and grass court surfaces. Such endeavours will be instrumental in facilitating more tailored and effective training programmes for athletes and coaches within the wheelchair tennis community.

Similarly, there is the need for further research that details the movement strategies and anatomical contributions from body segments to produce the physical demands of wheelchair tennis, in a population of athletes with a wide range of impairments and physical function.

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Conflict of interest BMP and MGTJ are employed by the KNLTB. CB is employed by the International Tennis Federation (ITF). BMP and SW are Heads of Classification of the ITF. CLA, NH, DCJvR, SM, MR, ASP, TS, LJS, RBS, RMAvdS, and NW have no conflicts of interest that are directly relevant to the content of this article.

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Consent to Participate Not applicable.

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Authors' contributions SW, BMP, MGTJ, SM, and NH conceived the idea for the study, while CLA, CB, MR, ASP, RBS, RMAvdS, and NW made substantial contributions to the study's design. LJS conducted the literature search with input from SW, MGTJ, and BMP. SW, BMP, and MGTJ screened the articles and extracted the data. TS analysed the data and conducted the statistical analysis and meta-analysis. SW, BMP, MGTJ, DCJvR, SM, and NH prepared the original draft. All authors helped critically revise the work for important intellectual content, approved the final version of the work, and agreed to be accountable for all aspects of the work.

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