

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

Sports Medicine

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Supplementary File 3. Characteristics of the included studies.

Study	Country	Design	Aim(s)	Setting	Sample size (n)	Matches (n)	Age (mean (SD)) (y)	Sex (male: n (%))	Playing level	Surface	Assessment tool	Comparison	Outcome measures
Bergeron 2007	USA	Pre-post	Examine core body temperature, sweat loss, pre- and post-play hydration	USTA National Boys' 14s Junior Championships	8	8	13.9 (0.9)	8 (100%)	National (junior)	Hard	Live observation	Pre-vs post-match	Match duration
Brown 2021	United Kingdom	Analytical cross-sectional	Determine association between serve speed and serve success	W 2004-2019	NR	2210	NR	NR (50%)	International	Grass	Match statistics, radar gun	Male vs female, 1 st vs 2 nd serves, serve speed vs serve success	1 st and 2 nd serve speed

Brown 2008	United Kingdom	Analytical cross-sectional	Describe nature of play since introduction of new balls	AO, RG, W, USO 2007	175	75 M, 69 F	NR	92 (53%)	International	Hard, clay, grass	Video-analysis	Men vs women; hard vs clay vs grass	Rally duration
Carboch 2017	Czech Republic	Analytical cross-sectional	Compare game characteristics on different surfaces	AO, RG, W, USO 2015-2017	NR	508 M, 508 F	NR	50%	International	Hard, clay, grass	Match statistics	Men vs women; hard vs clay vs grass	Sets/match games/match, games/set, points/match, points/set, points/game
Carboch & Placha 2018	Czech Republic	Analytical cross-sectional	Compare rally pace characteristics and shot frequency between early and late tournament stages	AO 2017	24	23	26.3 (4.4)	0 (0%)	International	Hard	Video-analysis	Early vs late tournament stage: 1st-4th round vs quarter finals to finals	Rally duration, rally pace, strokes/rally, work:rest ratio
Carboch 2018	Czech Republic	Analytical cross-sectional	Examine rally pace characteristics and shot frequency	AO 2017	39	7 M, 23 F	M: 28.0 (4.9) F: 26.8 (4.5)	12 (31%)	International	Hard	Video-analysis	Men vs women	Rally duration, rally pace, strokes/rally, work:rest ratio
Carboch 2019	Czech Republic	Analytical cross-sectional	Examine rally pace characteristics and shot frequency	AO, RG, W 2017	43	24	Hard 28 (4.9) clay 28.5 (3.5) grass 29.0 (5.3)	43 (100%)	International	Hard, clay, grass	Video-analysis	Hard vs clay vs grass	Rally duration, rally pace, strokes/rally, work:rest ratio
Carboch 2020	Czech Republic	Analytical cross-sectional	Examine new and used ball match characteristics and rally shot frequency	AO, RG, W 2017	85	24 M, 23 F	M Hard 28.0 (4.9) M Clay 28.5 (3.5) M Grass 29.0 (5.3) F Hard 26.8 (4.5)	58 (68%)	International	Hard, clay, grass	Video-analysis	New vs used balls	Rally duration, rally pace, strokes/rally, work:rest ratio

Cui 2017	Spain	Analytical cross-sectional	Explore differences in technical, tactical and movement performance based on player experience and relative quality	AO, RG, W, USO 2015-2017	1188	594	NR	1188 (100%)	International	Hard, clay, grass	Match statistics	Hard vs clay vs grass; low vs high player quality & experience	Distance/rally, distance/set, distance/match
Cui 2018	Spain	Analytical cross-sectional	Analyse and compare match performance; model relationship between variables and relative quality; build performance profiles	AO, RG, W, USO 2014-2017	257	1369	NR	0 (0%)	International	Hard, clay, grass	Match statistics	Australian Open vs French Open vs Wimbledon vs US Open	Distance /rally, distance/set, distance/match
Cui 2020a	Spain	Analytical cross-sectional	Explore indicators discriminating between seeded / non-seeded players	AO, RG, W, USO 2015-2017	433	549	NR	433 (100%)	International	Hard, clay, grass	Match statistics	Seeded vs non-seeded players	Distance/rally, distance/set, distance/match
Cui 2020b	Spain	Analytical cross-sectional	Analyse set-based differences in performance; explore set-to-set variation in performance	AO, USO 2016-2017	NR	146	NR	100%	International	Hard	Match statistics	1st vs 2nd vs 3rd vs 4th vs 5th set	Distance/rally, distance/set, distance/match
Fernández-Elias 2020	Spain	Cross-over trial	Determine effect of beetroot juice supplementation on movement patterns	Simulated match play, outdoor tennis facility	9	NR	24.9 (4.2)	9 (100%)	International	Hard	GPS	Beetroot juice vs placebo	Distance/min, peak speed, distance/min/speed zone, accelerations/match, decelerations/match
Fernandez-Fernandez 2007	Spain	Descriptive cross-sectional	Assess physiological load and patterns of	Invitational tennis tournament	8	7	17.3 (1.9)	0 (0%)	International	Hard	Video-analysis	Service vs return games	Change of direction/rally, effective playing

			match-play activity										time, rally duration, strokes/rally
Fernandez-Fernandez 2008	Spain	Descriptive cross-sectional	Determine match activity and physiological demands	Invitational tennis tournament	8	7	17 (2.4)	0 (0%)	International	Clay	Video-analysis	Service vs return games	Effective playing time, match duration, rally duration, strokes/rally, work:rest ratio
Filipic 2015	Slovenia	Analytical cross-sectional	Compare differences in match variables between groups of top players	Grand Slams and ATP tournaments in 1991, 2000, 2010	392	6984	NR	392 (100%)	International	Carpet, clay, grass hard	Match statistics	Positive vs negative win-loss nr of matches and year (1991, 2001, 2010)	Match duration
Filipic 2021	Slovenia	Analytical cross-sectional	Compare differences in math variables between juniors and professionals	U14 National Championships, ITF Men's World Tennis Tournament	16	6 4	13.9 (0.8) 20.1 (1.1)	16 (100%)	National (junior), International	Hard	Video-analysis, SAGIT Tennis tracking system	Junior vs professional	Effective playing time, match duration, rally duration, strokes/rally, strokes/match, distance per shot/rally/match, average/peak speed
Fitzpatrick 2019	United Kingdom	Analytical cross-sectional	Identify important match-play characteristics on clay / grass, for elite players	RG, W 2016, 2017	NR	984	NR	485 (49%)	International	Clay, grass	Match statistics	Winners vs losers	Mean first serve speed
Galé-Ansodi 2014	Spain	Analytical cross-sectional	Describe physical profile in match-play by analysis of accelerations / velocities	Aragon Tennis Master 2012, 2013	29	87	14.0 (2.9)	12 (41%)	National (junior)	Hard	GPS	1st-3rd vs 4th to 6th seed	Average/peak running speed, accelerations/match
Galé-Ansodi 2016	Spain	Analytical cross-sectional	Compare physical profile between clay and hard court for high-level young	Aragon Tennis Master and Nike Circuit Stadium Casablanca	14	40 M, 16 F	12.9 (1.3)	10 (71%)	National (junior)	Hard, clay	GPS	Hard vs clay	Acceleration distance/min, average speed, distance/

			players using GPS technology	Tournament 2014, 2015									min, distance/min/speed zone
Galé-Ansodi 2017a	Spain	Descriptive cross-sectional	Describe physical demands of match play in young players (velocity and acceleration using micro-technology)	Official outdoor matches from Aragon Tennis Federation	26	62	13.1 (1.8)	0 (0%)	National (junior)	Hard	GPS	Men vs women; high ranking vs low ranking	Average/peak speed, distance/match, distance/minute, match duration
Galé-Ansodi 2017b	Spain	Descriptive cross-sectional	Describe physical profiles in match play of young players using GPS technology considering gender and ranking	Aragon Tennis Master 2014-2016	29	49 M, 49 F	14.0 (2.9)	17 (59%)	National (junior)	Hard	GPS	Men vs women; high ranking vs low ranking	Acceleration distance/min, average/peak speed, distance/match, distance/minute, distance/min/speed zone
Galé-Ansodi 2018	Spain	Analytical cross-sectional	Compare running activity between training and match-play for young players	Aragon Tennis Master 2015	20	22 M, 18 F	13.8 (2.1)	10 (50%)	National (junior)	Hard	GPS	Match-play vs training	Acceleration distance/min, acceleration distance/min/speed zone, average/peak speed, distance/Minute, distance/minute/speed zone
Gallo-Salazar 2015	Spain	Randomised controlled trial	Determine effect of caffeinated energy drink on physical performance	Simulated match play on outdoor court	14	10 M, 4 F	16.36 (1.15)	10 (71%)	National (junior))	Hard	GPS	Caffeine vs placebo	Peak speed, distance/hour
Gallo-Salazar 2019	Spain	A repeated-measures and between-groups experimental design	Determine if game activity and physiological responses of young players differs based on session and	Simulated match play on outdoor court	12	12	14.5 (0.8)	12 (100%)	National (junior)	Hard	GPS	Morning vs afternoon; winners vs losers	Accelerations/match, average/peak speed, distance/minute, distance/speed zone/min,

			match outcome during simulated competition										distance/speed zone/match, effective playing time, match duration, rally duration, strokes/rally, work:rest ratio
Giles 2021	Australia	Analytical cross-sectional study	Explore movement styles related to change of direction	AO 2016-2018	139	513	NR	62 (44.6%)	International	Hard	GPS	Male vs. female	Change of directions per match
Hoppe 2014	Germany	Analytical cross-sectional	Assess running activities during match play, characterise changes during course of match and identify differences between winners and losers	Simulated match play against opponent of similar ability on outdoor court	20	10	13 (1)	20 (100%)	National (junior)	Clay	GPS	Winner vs loser; 1st vs 2nd vs 3rd vs 4th period of the match	Average speed, distance/match, match duration, peak speed, distance/speed zone, accelerations & decelerations/match, accelerations & decelerations/min
Hoppe 2016	Germany	Analytical cross-sectional	Investigate differences in running activities between adolescent and adult players and winners and losers in each age group	Simulated match play against opponent of similar age and ability on outdoor court	40	20 jr, 20 sr	13 (1) 25 (4)	40 (100%)	National (junior) Regional (senior)	Clay	GPS	Adult vs junior; winners vs losers	Average/peak speed, distance/match, distance/speed zone, accelerations& decelerations/ match
Hornery 2007	Australia	Analytical cross-sectional	Examine physiological responses to match play and influence on match notation and performance variables	2003/2004 Australian summer/autumn tennis circuit,	12	12	21.4 (2.6)	12 (100%)	International	Hard, clay	Video-analysis, radar gun	Hard vs clay	Changes of direction/rally, match duration, rally duration, strokes/rally

Johnson 2005	USA	Descriptive cross- sectional	Determine performance demands (stroke number/type) on different surfaces	RG, W, USO, 2003	28	NR (only games)	NR	28 (100%)	International	Hard, clay, grass	Video- analysis	Hard vs clay vs grass; service vs return games	Backhand slice/game, topspin/ game, forehand slice/game, forehand topspin/game, overheads/ game, strokes/game, serves/game, volleys/game
Kilit 2017	Turkey	Analytical cross- sectional	Compare physiological responses and time-motion characteristics between serve vs. return games and winners vs. losers during simulated match play	Simulated matchplay on outdoor court	28	14	12.2 (0.3)	28 (100%)	National (junior)	Clay	GPS, video analysis	Serve vs return games; winners vs losers	Distance/match, distance/ speed zone, effective playing time, games/match, rallies/match, match duration, rally duration, strokes/rally, work:rest ratio
Kilit 2018	Turkey	Randomized cross-over design	Assess influence of surface on psychophysiological responses, time-motion and match characteristics of young players	Simulated matchplay on outdoor court	52	26	13.0 (0.3)	52 (100%)	National (junior)	Hard, clay	GPS, video- analysis	Hard vs clay	Average speed, distance/match, effective playing time, rally duration, strokes/rally, work:rest ratio
Klaassen 1998	Netherlan ds	Analytical cross- sectional	Challenge independent- and-identically- distributed- assumption and proposes a model for conditional probability of winning a point on service	W 1992-1995	NR	258 M, 223 F	NR	appr 54%	International	Grass	Match statistics	Men vs women	Rallies/match, rallies/set, rallies/game, sets/match, games/set, games/match, points/tiebreak

Kovalchik 2017	Australia	Analytical cross-sectional	Describe age/competition profile of elite junior players; contrast match, game and shot characteristics; compare factors associated wins	AO 2012-2017	NR	21 M (sr), 12 M (jr), 21 F (sr), 6 F (jr)	NR	appr 55%	International	Hard	Match statistics, Hawk-eye	Men vs women; junior vs senior	Change of direction/rally, distance/match, distance/rally, peak speed, rally duration, serves/match, forehands/match, backhands/match
Lisi 2021	Italy	Analytical cross-sectional	Analyse factors impacting match length and propose a model to simulate match durations	Grand Slams, ATP1000, ATP500, ATP250 2011-2018	NR	19961	NR	100%	International	Hard	Match statistics	Best of 5 vs best of 3	Match duration
Mackie 2013	United Kingdom	Analytical cross-sectional	Compare work:rest ratio between top male and female players	ATP World Tour Finals and WTA End of Season Championships 2012	8 M, 8 F	9 M, 9 F	NR	8 (50%)	International	Hard	Video-analysis	Men vs women	Match duration, rally duration, work:rest ratio,
Maquirriain 2016	Argentina	Analytical cross-sectional	Analyse serve speed and accuracy in 5-set matches	W, 2015	30	15	NR	50 (100%)	International	Grass	Match statistics	1st vs 2nd vs 3rd vs 4th vs 5th set	Distance/match, match duration, mean 1 st and 2 nd serve speed
Martínez-Gallego 2013	Spain	Analytical cross-sectional	Analyse distance covered in relation to groundstroke direction and if differences exist between winners / losers	ATP500 Valencia 2011	11	8	NR	11 (100%)	International	Hard	SAGIT tennis tracking system, video-analysis	Winners vs losers	Average speed, distance/game
Martínez-Gallego 2019	Spain	Analytical cross-sectional	Establish differences between point winners and point losers in movement volume/intensity	ATP500 Valencia 2011	11	8	NR	11 (100%)	International	Hard	SAGIT tennis tracking system, video-analysis	Winners vs losers	Average speed, distance/rally, rally duration

			according to position										
McCarthy 2002	United Kingdom	Pre-post	Assess fluid loss during match play	Junior county tournament	20	NR	12-14 y	14 (70%)	Regional (junior)	Hard	Live observation	Pre vs. Post-match	Match duration
Meffert 2019	Germany	Analytical cross-sectional	Investigate performance parameters during situations requiring greater mental strength, e.g., tiebreaks	W 2016	128	64	NR	128 (100%)	International	Grass	Match statistics	Tiebreak points vs non-tiebreak points	Rally duration
Mendez-Villanueva 2007	Spain	Descriptive cross-sectional	Examine activity patterns, BL, PE during singles match play	ATP	8	7	27 (4.4)	8 (100%)	International	Clay	Video-analysis	Serving vs receiving	Effective playing time, match duration, rally duration, strokes/rally, work:rest ratio
Morante 2005	Australia	Descriptive cross-sectional	Assess activity patterns / performance during singles competition	AO, W 2005	44	24 M, 18 F	NR	26 (59%)	International	Hard, grass	Television broadcast or live observation	Hard vs grass, male vs. female	Effective playing time, game duration, match duration, rally duration, strokes/minute
Moreno-Pérez 2019	Spain	Pre-post	Examine acute effect of competitive match on bilateral passive shoulder range and strength*	Simulated matchplay on outdoor court at two Spanish Tennis Academies	26	13	20.4 (4.4)	26 (100%)	International	Hard	Video-analysis, radar gun	Hard	Match duration
Murphy 2016	Australia	Repeated measures experimental design	Compare characteristics of drill-based training to match play; compare training loads in matches won versus lost and between seeded/	Two Australian national-title events and two junior ITF events 2014/2015	28	90-126 (M), 19-144 (F)	16 (1.1)	10 (36%)	International	Hard	Video-analysis	Training vs competition	Match duration, strokes/minute, work:rest ratio

			non-seeded players										
Myers 2016	USA	Analytic cross- sectional	Develop volume- based interval training program	USO 2013/2014, 2014 Orange Bowl	527	M 269, F 258	NR	269 (51%)	International	Hard, clay	Match statistics	Men vs women, juniors vs seniors	Serves /match, Serves/set
O'Donoghue 2001	United Kingdom	Analytical cross- sectional	Determine if sex / surface effects player strategies	AO, RG, W, USO 1997-1999	169	107 M, 68 F	NR	107 (63%)	International	Hard, clay, grass	Video- analysis	Men vs women, hard vs clay vs grass vs hard	Rally duration, strokes/second
O'Donoghue 1998	United Kingdom	Analytical cross- sectional	Determine if introduction of slower / faster balls resulted in similar games	RG, W 1996	54	23 M, 21 F		26 (28%)	International	Clay, grass	Video- analysis	Men vs women; French Open vs Wimbledon	Effective playing time, rally duration,
Pereira 2017	Brazil	Analytical cross- sectional	Analyse physical / technical demands of official matches	ATP Futures, Brazil	8	4	NR	8 (100%)	International	Clay	Video- analysis, automatic tracking	1st vs 2nd set	Distance/match distance/set, distance/game, distance/rally, distance/minute
Pereira 2016	Brazil	Analytical cross- sectional	Compare kinematic characteristics of matches	Simulated match play, Brazil	8	8	15.5 (1.2)	8 (100%)	National (junior)	Hard, clay	GPS	Clay vs hard court	Distance/speed zone/match, accelerations / speed zone/ match
Perri 2018	Australia	Analytical cross- sectional study	Evaluate differences in training loads at three distinct developmental levels	ITF tournaments, Australia	39	M: 11 U12, 5 U15, 5 U18, F: 12 U12, 3 U15, 3 U18	M: 11.6 (0.7), 14.0 (1.1), 17.0 (1.1); F: 12.0 (1.0), 14.0 (0.6), 17.3 (0.6)	21 (54%)	National (junior)	Hard	GPS, video- analysis	U12 vs U15 vs U18, men vs women	Distance/match, distance/minute, match duration
Ponzano 2017	Italy	Analytical cross- sectional	Analyse movement variables, metabolic model, and potential surface-related differences (using	Simulated match play on outdoor courts at two different tennis centers, Italy	24	12 M 12 F	16 (3)	12 (50%)	National (junior)	Hard, clay	GPS	Hard vs clay	Match duration

			GPS and HR monitors)										
Reid 2016	Australia	Analytical cross-sectional	Synthesise player and ball Hawk-Eye data to compare in-match movement and stroke characteristics	AO 2012-2014	197	M 88 F 82	NR	102 (52%)	International	Hard	Hawk-Eye	Men vs women	Distance/match, distance/set, distance/game, strokes/game, serves/game, forehands/game, backhands/game
Reilly 1994	United Kingdom	Descriptive cross-sectional	Determine work-rate / physiological response to indoor matches	Simulated match play, indoors	8	4	23.4 (3.1)	8 (100%)	Regional	Wooden	Video-analysis	Not applicable	Match duration, effective playing time, games/match, rally duration, work:rest ratio
Sánchez-Pay 2021	Spain	Analytical cross-sectional	To analyse differences between winning en losing players and between tournaments	AO, RG, W, USO 2017-2018	NR	248	NR	0 (0%)	International	Hard, clay, grass	Hawk-Eye	AO, vs RG vs W vs US, winners vs. losers	Match duration, sets/match, games/set
Smith 2018a	Australia	Analytical cross-sectional	Determine effect of environmental conditions on heat-related court calls, behavioural responses and match characteristics	AO 2014-2016	189	360	25 (4)	0 (0%)	International	Hard	Match statistics	Per ACSM WBGT zones	Match duration, fastest serve speed, average 1 st and 2 nd serve speed, rallies/match
Smith 2018b	Australia	Analytical cross-sectional	Determine effect of environmental conditions on heat-related court calls, behavioural responses and match characteristics	AO 2014-2016	189	360	27.8 (3.8)	189 (100%)	International	Hard	Match statistics	Per ACSM WBGT zones	Match duration, fastest serve speed, average 1 st and 2 nd serve speed, rallies/match
Stare 2015	Slovenia	Analytical cross-sectional	Determine performance success (serve, return of serve	U14 National Championships, indoor ATP tournament	28	6 M (jr) 5 F (jr) 5 M	M (jr) 13.8 (0.7), F (jr) 14.1 (0.5), M 18.3 (4.7)	18 (64%)	National (junior), international	Hard	SAGIT tennis tracking system,	ATP vs boys vs girls	Effective playing time, match duration, rally duration,

			and baseline game)								video-analysis		strokes/match, strokes/rally, rallies/match
Takahashi 2006	Japan	Analytical cross-sectional	Validate scorebook and clarify characteristics of tactics	AO, RG, W 2003-2004	82	41	NR	82 (100%)	International	Hard, clay, grass	Live analysis with computerised scorebook	French Open vs Wimbledon vs US Open	Rally duration, strokes/rally, rally pace
Takahashi 2009	Japan	Analytical cross-sectional	Analyse time factors in singles matches using computerised scorebook	AO, RG, W 2003-2004	82	41	NR	82 (100%)	International	Hard, clay, grass	Live analysis with computerised scorebook	French Open vs Wimbledon vs US Open	Rally pace 1st serve, 2nd serve, ground stroke
Torres-Luque 2011	Spain	Descriptive cross-sectional	Analyse temporal structure of individual play	National junior	32	8 M 8 F	15.6 (0.9)	16 (50%)	National (junior)	Hard	Video-analysis	Men vs women	Effective playing time, match duration, work:rest ratio
Whiteside & Reid 2017	Australia	Descriptive cross-sectional	Quantify external workloads (strokes played, distance covered, movement speed) during first tournament week	AO 2012-2014	29	52 M 64 F	NR	13 (45%)	International	Hard	Hawk-Eye	Men vs women; 1st vs 2nd vs 3rd vs 4th round	Accelerations/match, distance per game/match/speed zone, effective playing time, strokes/forehands/backhands/serves/volleys/overheads per game/match
Whiteside 2015	Australia	Analytical cross-sectional	Utilize Hawk-Eye data to compare performance of top / lower-ranked players	AO 2012-2014	118	80	NR	118 (100%)	International	Hard	Hawk-Eye	Top-ranked vs lower-ranked players	Average/peak speed, distance/match, distance /rally, rally duration
Yusoff 2021	Malaysia	Analytical cross-sectional	Compare junior and elite players	International semi-finals and finals in 2016-2017	NR	7 Junior 7 elite	NR	100%	International	NR	Video-analysis	Junior vs elite	Match, set & rally duration, rallies/set, strokes/rally, work:rest ratio,

ACSM: American College of Sports Medicine; AO: Australian Open; BL: Blood Lactate; GPS: Global Positioning System; ITN: International Tennis Number; Jr: Junior; HR: Heart Rate; NR: Not Reported; PE: Perceived Exertion; RG: Roland Garros; USO: US Open; WBGT: Wet Bulb Globe Temperature; W: Wimbledon.

* Rotation Range of Motion, Isometric External (ER) Rotation and Internal Rotation (IR) strength, ER/IR isometric strength ratio and serve speed in dominant and non-dominant side.