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Using markerless motion analysis to quantify sex and discipline differences in external mechanical work during badminton match play

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ABSTRACT

The high prevalence of overuse injuries in badminton poses a major threat to player development and success, with current training ‘load’ metrics insufficient for capturing the physical demands. This study quantified the external mechanical work performed during badminton match play across different sexes and disciplines. An eight-camera system captured fourteen male and fourteen female competitive (University to national level) badminton players competing across a total of nine singles and six doubles matches. Markerless pose estimation (HRNet) was used to drive a kinematic model (OpenSim) of each player and compute mass-normalised external mechanical work and power for 30 points per match. A linear mixed effects model found normalised work and power to be greater in men’s vs. women’s matches (effect size [ES] ± 90% CI = 0.60 ± 0.29 and 1.10 ± 0.48, respectively). Normalised work and power were also greater in singles vs. doubles matches (ES = 0.44 ± 0.29 and 0.47 ± 0.44, respectively). Interestingly, discipline differences were greatest among the most skilled players (e.g. ES = 0.88 ± 0.49 for first-team males). These findings highlight the importance of additional strength training and adequate recovery for elite male players to manage the high physical demands of singles match play.

KEYWORDS

Racket sports; training load; player tracking

Introduction

Badminton is a fast-paced, non-contact racket sport, characterised by intermittent bursts of high-intensity rallies and is both technically and physically demanding (Cabello Manrique & Gonzalez-Badillo, 2003; Faude et al., 2007). Since its official introduction to the Olympic Games in 1992, badminton’s popularity has risen rapidly, with global estimations of active players and fans exceeding 339 and 735 million, respectively (Badminton World Federation, 2019). Within the sport of badminton, lunges, jumps and rapid accelerations are fundamental in achieving advantageous positioning and play a key role in determining rally outcomes (Valldecabres et al., 2020). During these movements, ground reaction forces can reach up to three times a player’s bodyweight (Lam et al., 2018), exposing the knee joint to significant loads, particularly in male players. This accumulation of tissue damage through repeated loading (coupled with insufficient recovery) is associated with overuse injury (Brenner et al., 2024). In fact, lower-limb overuse injuries (e.g., patellar and achilles tendinopathy) are the most common injury in the sport of badminton, making up 58.0–92.3% of total injuries, which occur at an overall rate of 0.9–7.4 injuries per 1000 hours of participation (Pardiwala et al., 2020; Phomsoupha & Laffaye, 2020). Importantly, the time loss caused by such injuries can have both negative health and financial consequences (Haugen, 2022), highlighting the need for targeted efforts to reduce the high injury incidence in badminton.

Training stimuli induce cellular disturbances within tissue (Coffey & Hawley, 2007) that, when coupled with adequate

recovery, lead to ‘functional overreaching’, which involves the restoration or super-compensation of performance through tissue remodelling (Bellinger, 2020). However, when adequate recovery is absent for a given stimulus, overreaching can become non-functional, and decreases in performance can persist, accompanied by an increased risk of injury (Kibler et al., 1992; Soligard et al., 2016).

Staying within one’s functional capacity whilst maximising adaptations is a challenge for athletes and coaches, but one that has the potential to be overcome through the quantification of training stimuli (Halson, 2014). This is often done using the term ‘training load’, which can be thought of as the input variable to a training system, used to elicit desired training responses (Coutts et al., 2017). Training load can be divided into two main components: external and internal load. External load refers to the physical work prescribed in training and is determined by the structure, quality, and quantity of exercise (Impellizzeri et al., 2019). Internal load encompasses the psychophysiological responses to training, such as heart rate or rating of perceived exertion (Impellizzeri et al., 2005). In the context of overuse injuries, a focus on external load is required to capture the demands placed upon the musculoskeletal system during on-court movement.

To date, existing literature quantifying external load in badminton has focused on shots per rally (Ming et al., 2008), rally duration (Fernandez-Fernandez et al., 2013) and distance covered (Abdullahi et al., 2019). While these metrics provide some insight into total training volume, they do not capture the

mechanical demands of movement. These can instead be measured through external mechanical work, the work done to move the centre of mass (CoM) through a displacement (Donelan et al., 2002). External mechanical work reflects the changes in the mechanical energy of a body across time, with the rate of mechanical work done (i.e., mechanical power) also providing crucial insight into the energetic demands of movement (Peyré-Tartaruga et al., 2021).

Marker-based motion capture is considered the *de facto* standard to measure external mechanical work on the CoM and has been used to measure external mechanical work during lunge and jump drills in badminton (Kersting et al., 2018). However, its need for skilled, time-consuming, and potentially obtrusive marker placement limits its use in applied settings (Moro et al., 2022) and somewhat explains why external mechanical work is yet to be measured during badminton match play. Nonetheless, with the emergence of markerless technologies (which utilise deep learning-based computer vision algorithms to identify key points in images), there are new opportunities to unobtrusively measure joint positions (Kanko et al., 2021; Needham et al., 2021) and angles (Kanko et al., 2021; Needham et al., 2022; Pagnon et al., 2021), with good agreement compared to traditional marker-based approaches. In fact, Emmerson et al. (2023) have recently shown that the external mechanical work completed during tennis strokes can be accurately measured using markerless motion capture approaches. Thus, laborious and costly setups are no longer needed for measuring external mechanical work, reducing the barrier to entry and enabling wider adoption of this technology.

Whilst injury epidemiological data in badminton are scarce, a study of competitive university-level players found greater overall incidence rates in female vs. male players (5.1 and 2.5 per 1000 hours of training, respectively) (Miyake et al., 2016), with lower-limb overuse injuries being the most common injury (Pardiwala et al., 2020). Therefore, it seems key that coaches are able to accurately quantify the work individual players complete during training and competition. By doing so, they can appropriately alter training practices and recovery strategies accordingly for male and female players, as well as singles and doubles players. Men's badminton matches are typically more intense than women's, with more shots per rally (6.4 vs. 4.7) and greater rally durations (6.8 vs. 5.7 s) in elite junior competition (Fernandez-Fernandez et al., 2013). Notational analyses during elite international competitions have also indicated that the men's matches tend to involve more intense bouts of exercise (Abian-Vicen et al., 2013; Gomez et al., 2019; Rojas-Valverde et al., 2020; Valldecabres et al., 2016). Similarly, higher-level matches are typically more physically demanding than those at lower levels, regardless of sex (Heller, 2010; Leong & Krasilshchikov, 2016). Interestingly, however, Fu et al. (2017) found relative 'player load' (a commonly-used, accelerometry-based 'workload' metric) to be similar across males and females. Whilst notational analyses can provide an overview of differences in match characteristics, such analysis does not provide insight into the mechanical energy that is expended during the game play. A non-invasive tool that can monitor players' 'workload' during

training and competition could therefore provide important insight into the demands of badminton match play.

Average heart rate is typically greater during men's singles ($88.8 \pm 5.2\%$ of maximum heart rate [HR_{MAX}]) than doubles ($75.5 \pm 8.8\%$ HR_{MAX}) (Alcock & Cable, 2009) and for both sexes, more jumps (+40%) and lunges (+250%) per player have been observed in singles vs. doubles matches (Le Mansec et al., 2023). Within a women's doubles team, individual player roles are balanced and physical demands similar regardless of position (Le Mansec et al., 2023). However, in men's doubles, it is typical for one player to perform significantly more jumps (+23%) and smashes (+48%) than their teammate (Le Mansec et al., 2023). Position rotation between rallies to accommodate for this is common, but each rally can vary drastically and there is potential for large differences in external mechanical work to develop between teammates across the entirety of a match. Failing to recognise and act on these differences between individuals could result in the over or under-estimation of the work performed by doubles partners.

The aim of this study, therefore, was to use markerless motion capture to quantify the external mechanical work and the rate of external mechanical work (i.e., mechanical power) performed during badminton match play and investigate the differences between sexes and disciplines. It was hypothesised that external mechanical work and power would be greater in men's vs. women's matches, and greater in singles vs. doubles for both sexes.

Materials and methods

Participants

To detect an expected sex effect size (ES) of 1.0 (based on mean effect on rally duration, resting time and strokes per rally; Fernandez-Fernandez et al., 2013), an *a priori* power analysis (with power=0.8 and $\alpha=0.05$) revealed that 14 males and 14 females should be recruited for this study. Participants were competitive University-level badminton players (Table 1), who met the criteria for tier 2 (trained/developmental; $n=6$) or tier 3 (highly trained/national level; $n=22$) of the participant classification framework proposed by McKay et al. (2022). Specifically, this sample comprised 15 first-, 7 second- and 6 third-team University players (with the first team being the highest-level players). Players competed against and/or partnered with players of the same tier as themselves. Players with pre-existing or current injuries that may have worsened during match play did not participate. This study was approved by the University of Bath Research Ethics Committee (reference approval number: 1485–1689)

Table 1. Participant characteristics and breakdown of matches played.

	Males ($n=14$)	Females ($n=14$)
Age (yr)	20.5 ± 1.6	19.8 ± 1.2
Height (m)	1.78 ± 0.07	1.65 ± 0.06
Mass (kg)	72.3 ± 11.4	63.7 ± 10.7
Total number of singles matches (players analysed)	5 (10)	4 (8)
Total number of doubles matches (players analysed)	3 (12)	3 (12)

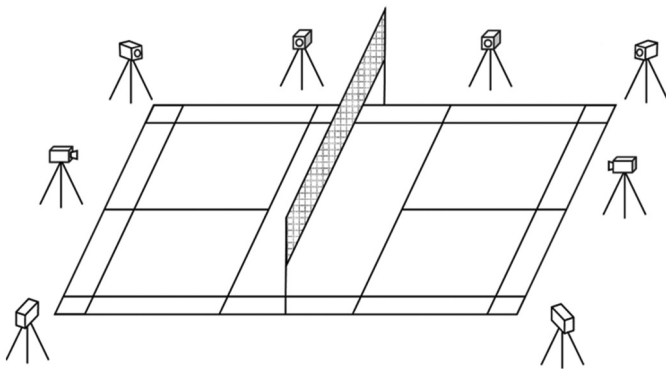


Figure 1. Camera placement around the badminton court.

and participants provided informed consent prior to participation. Participants completed one match in singles and/or doubles (14 players played in both, 4 played only singles and 10 played only doubles).

Experimental procedure

An eight-camera (JAI sp5000c, JAI Ltd, Denmark) setup (Figure 1) was used to capture synchronised footage (200 hz) of 30 rally points across each match. It was not possible to capture every consecutive point due to long saving times of the video footage.

Camera placement ensured large capture volumes and multiple views of the court, providing robustness against occlusions. Calibration was performed by moving a binary dot matrix through the capture volume to initialise each camera's intrinsic parameters, lens distortion coefficients and extrinsic parameters, which were then globally optimised using a sparse bundle adjustment (Zhang, 2000). Prior to match play, a static trial, required for OpenSim model scaling, was recorded. Participants performed their usual warm up and were then instructed to play as normal to simulate standard match play, with players taking self-selected rest periods.

Data processing

The video data were processed according to the workflow of Needham et al. (2022). Briefly, 2D pose estimation (using a pre-trained HRNet model; Sun et al., 2019) provided 17 sparse key point locations from each camera image. Players were identified and tracked by using an occupancy maps approach to associate individual detections across camera views and over time. 2D poses were then fused to reconstruct individuals in 3D and a bi-directional Kalman filter was applied. Key point 3D coordinates were then used to drive the motion of a constrained OpenSim model, which was based on Rajagopal et al. (2016) with adapted scapulothoracic joints (Seth et al., 2016) and articulated neck joint (Cazzola et al., 2017). Each model was scaled using its associated static trial, and segment mass and inertia properties were set to those from de Leva (1996). The OpenSim inverse kinematics tool was used to find the globally-optimised pose. Joint angles were filtered using a low-pass, fourth-order Butterworth filter with a cutoff

frequency of 6 Hz, determined by a residual analysis. Previous analyses have shown good agreement between this markerless pipeline and kinematic outputs derived through marker-based approaches (Needham et al., 2022).

The full body kinematics were then used to compute the mechanical work and power for each point and each player in Python 3.12 (available from: <https://github.com/FilippoO2/OpenSim-Kinematics-Analysis>). Full body kinematics were cropped from the start to end frame of each rally, determined manually as the initiation and cessation of player movement, respectively. Changes in total mechanical energy (potential + kinetic energy) were calculated using CoM kinematics. Across the duration of each rally, positive and negative external mechanical work were calculated as the sum of the increments and decrements in total mechanical energy, respectively (Pavei et al., 2017). To capture movement intensity, average mechanical power was calculated by dividing external mechanical work by rally duration. Mass-normalised mechanical work ($J \cdot kg^{-1}$) and power ($W \cdot kg^{-1}$) were then computed to account for differences in body mass between participants. CoM kinematics were further utilised to compute 'player load', using the equation of Boyd et al. (2011), and distance covered per point.

A notational analysis was conducted to provide additional context of captured play and facilitate comparative analyses to previous literature (Fernandez-Fernandez et al., 2013; Ming et al., 2008). Alongside temporal measures (rally and rest duration), number of shots, shot frequency, and the number of lunges, jumps and overhead shots (contact above head level) during each rally were recorded manually (and verified by a different member of the research team).

Statistical analysis

Shapiro-Wilk normality tests were utilised to assess the normality of the data prior to statistical analyses. A linear mixed effects model was applied in R (R Core Team, 2024) to investigate differences in normalised mechanical work and power across the 30 rally points between sexes, disciplines and abilities (determined by the team the player represented). Fixed effects included sex, discipline, ability and rally point number. The nested random effects were match and participant number, to account for the variability between matches and across individuals in the matches. Pairwise comparisons for players of different sex, discipline and ability were conducted and *p*-values were adjusted using the false discovery rate method to control error rates and maximise statistical power. Cohen's *d* ES and 95% confidence intervals (CI) were calculated and interpreted using the following thresholds: > 0.2 (small), > 0.5 (moderate) and > 0.8 (large). Mean values were adjusted by the model and reported as estimated marginal means.

Results

Notational analysis

Rally durations across sexes and disciplines did not significantly differ (Table 2). However, closer examination of results across abilities revealed that rallies were longer in

Table 2. Match characteristics across disciplines and sexes. Values are reported as estimated marginal means (EMM) per rally point with 95% confidence intervals (CI).

	Males				Females			
	Singles		Doubles		Singles		Doubles	
	EMM	95% CI	EMM	95% CI	EMM	95% CI	EMM	95% CI
Rally	6.50	5.68–7.32	5.37	4.49–6.26	5.59	4.74–6.43	5.89	5.00–6.78
Duration (s)								
Rest Time (s)	8.85	7.81–9.88	8.71	7.57–9.86	9.07	8.03–10.11	8.69	7.54–9.84
Work : Rest Ratio	0.67	0.52–0.83	0.66	0.50–0.83	0.62	0.46–0.77	0.73	0.56–0.89
Shot Frequency (s ⁻¹) *^	0.97	0.92–1.02	1.10	1.05–1.16	0.80	0.74–0.85	1.01	0.95–1.10
Lunges *^	0.90	0.78–1.03	0.33	0.19–0.46	0.53	0.40–0.66	0.24	0.11–0.38
Jumps ^	0.56	0.37–0.76	0.30	0.08–0.51	0.68	0.48–0.89	0.27	0.05–0.48
Overhead Shots ^	0.94	0.69–1.19	0.43	0.15–0.70	0.97	0.72–1.23	0.49	0.22–0.77
'Player load' (AU) *	83.2	69.6–96.8	94.9	80.1–109.7	61.7	47.7–75.7	67.9	53.0–82.7
Distance Covered (m) *^	9.54	8.38–10.71	5.30	5.92–8.32	7.12	4.03–6.57	4.55	3.28–5.82

*denotes statistically significant effect of sex. ^denotes statistically significant effect of discipline.

first team (7.24 s, 95% CI=6.10–8.38) and second team (6.71 s, 95% CI=5.06–8.37) male singles. Similarly, while overall rest durations were similar, the longest rest durations were observed in first team female singles (9.93 s, 95% CI=7.94–11.92). For that reason, work to rest ratios were highest and lowest in first team male and female singles, respectively.

Shot frequency was highest during male and doubles match play with the greatest value observed in second team men's doubles (1.12 per second, 95% CI=1.02–1.21). Per rally, significantly more lunges, jumps and overhead shots were performed in singles than doubles. There was no difference between sexes in jumps and overhead shots, but males performed significantly more lunges. First team males during singles performed the most lunges (1.01 per point, 95% CI=0.90–1.25) whilst third team females performed the most jumps (0.88 per point, 95% CI=0.48–1.28) and overhead shots (1.20 per point, 95% CI=0.74–1.65). Greater distances were covered by males during singles, particularly by those in the first team (10.48 m, 95% CI=8.85–12.10) and second team (10.24 m, 95% CI=7.90–12.58). The smallest distances were covered by females playing doubles across all abilities (4.55 m, 95% CI=3.28–5.82). 'Player load' was greater in males but similar across disciplines.

Normalised mechanical work and power

There was a direct relationship between positive and negative outputs, meaning results are discussed here with reference to positive values only. Normalised mechanical work and power were significantly greater in males than females with moderate and large effects, respectively (Table 3). In singles, normalised mechanical work and power were greater with a small effect size, though this was not statistically significant for power. A higher ability had a significant trivial effect on increasing normalised mechanical work but was not significant for normalised mechanical power.

Effect of sex

Men's match play required more normalised mechanical work than women's in both singles (ES = 0.74 ± 0.39, p = .001) and doubles (ES = 0.45 ± 0.41, p = .030) (Figure 2). Sex differences were greatest among first team singles (ES = 1.01 ± 0.63, p = .004), followed by second team singles (ES = 0.95 ± 0.60, p = .002). The effect of sex was smallest among third team singles (ES = 0.27 ± 0.56, p = .330) and doubles (ES = 0.31 ± 0.41, p = .120).

Table 3. The main effects of sex, discipline and ability on normalised mechanical work and power, and the linear mixed model statistics. Values reported are estimated differences and effect sizes (ES) with 95% confidence intervals, and p-values. Negative estimated differences for sex indicate values were lower in females, for discipline they indicate values were lower in doubles, and for ability they indicate values were lower at higher abilities.

	Factors						Model statistics			
	Sex		Discipline		Ability		ICC	R ² Marginal	R ² Conditional	AIC
	Estimated Difference	ES	Estimated Difference	ES	Estimated Difference	ES				
Work (+ve) (J·kg ⁻¹)	-9.28 (-13.41 to -5.16)	0.60 (0.31 to 0.89)	-7.26 (-11.45 to -3.07)	0.44 (0.15 to 0.72)	6.02 (2.46 to 9.58)	0.16 (0.08 to 0.40)	0.03	0.11	0.11	9707.3
Power (+ve) (W·kg ⁻¹)	-0.96 (-1.51 to -0.41)	1.10 (0.64 to 1.58)	-0.29 (-0.84 to 0.27)	0.47 (0.03 to 0.91)	0.41 (-0.06 to -0.89)	0.15 (-0.21 to 0.52)	0.03	0.11	0.14	9707.5
Work (-ve) (J·kg ⁻¹)	9.25 (5.20 to 13.30)	0.58 (0.30 to 0.87)	7.44 (3.33 to 11.54)	0.44 (0.16 to 0.71)	-5.91 (-9.40 to -2.42)	0.17 (-0.07 to 0.40)	0.10	0.24	0.32	3652.1
Power (-ve) (W·kg ⁻¹)	0.95 (0.42 to 1.47)	1.10 (0.63 to 1.57)	0.32 (-0.22 to 0.86)	0.49 (0.06 to 0.93)	-0.40 (-0.86 to 0.06)	0.18 (-0.18 to 0.54)	0.11	0.24	0.32	3706.6

Bold denotes statistically significant (p < .05). ICC = Intraclass Coefficient. AIC = Akaike Information Criterion.

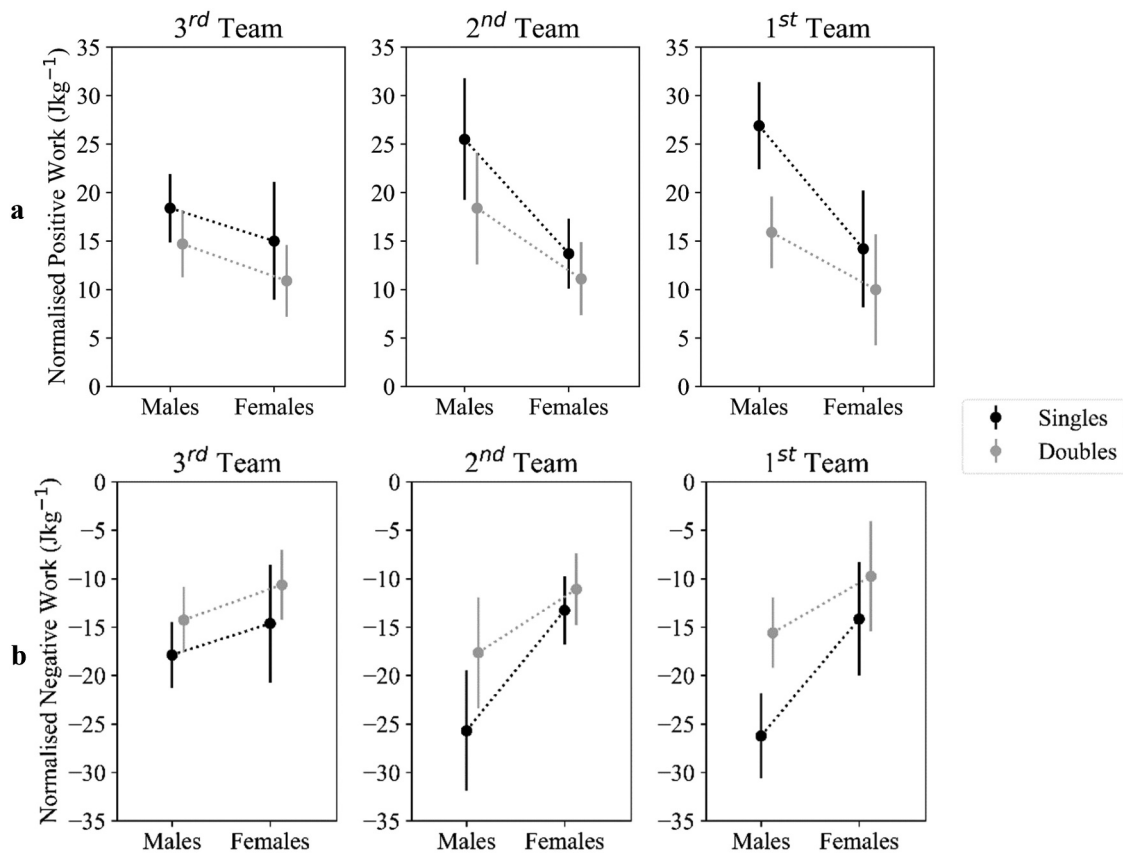


Figure 2. Normalised positive (A) and negative (B) mechanical work for each sex, discipline and ability. Data are represented as estimated marginal means and 95% CI.

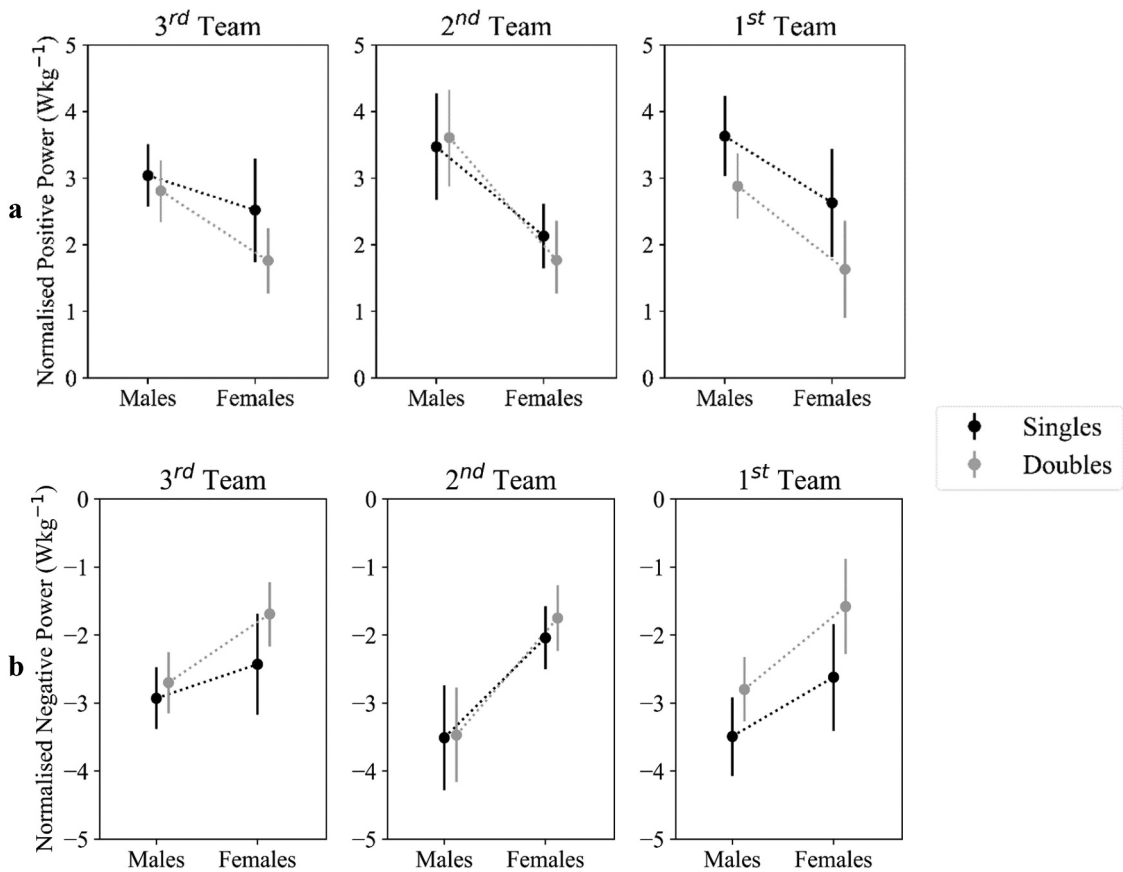


Figure 3. Normalised positive (A) and negative (B) mechanical power for each sex, discipline and ability. Data are represented as estimated marginal means and 95% CI.

Similarly to mechanical work, normalised mechanical power was greater in men's singles ($ES = 0.91 \pm 0.60$, $p = .005$) and doubles ($ES = 1.31 \pm 0.30$, $p = .001$) (Figure 3). Sex differences were largest in first team ($ES = 1.43 \pm 0.85$, $p = .051$) and second team players ($ES = 1.51 \pm 0.65$, $p < .001$). The effect of sex within the third team players was small and not statistically significant ($ES = 0.40 \pm 0.84$, $p = .234$).

Effect of discipline

Normalised mechanical work during singles was significantly greater with a moderate effect in males ($ES = 0.58 \pm 0.39$, $p = .007$) but not females ($ES = 0.29 \pm 0.39$, $p = .124$). Largest discipline differences were seen in first team males ($ES = 0.88 \pm 0.49$, $p = .001$) and second team males ($ES = 0.57 \pm 0.68$, $p = .095$). Females had significantly greater normalised mechanical power outputs in singles than doubles ($ES = 0.67 \pm 0.62$, $p = .035$), with largest differences in first and third team players ($ES = 0.95 \pm 1.03$, $p = .070$ and $ES = 0.72 \pm 0.87$, $p = .098$, respectively). Conversely, the overall effect of discipline in males was smaller and non-significant ($ES = 0.27 \pm 0.60$, $p = .342$). However, the effect of discipline within first team males was moderate, though not statistically significant ($ES = 0.72 \pm 0.75$, $p = .055$).

Effect of ability level

Ability had a small and significant effect on normalised mechanical work in males ($ES = 0.39 \pm 0.26$, $p = .010$) but was trivial and non-significant in females ($ES = 0.07 \pm 0.40$, $p = .880$). Though both were not statistically significant, the effect of ability was greater in singles ($ES = 0.31 \pm 0.40$, $p = .320$) than doubles ($ES = 0.01 \pm 0.27$, $p = .930$). The largest effect was in male singles, with first team males performing more normalised mechanical work than third team males ($ES = 0.68 \pm 0.47$, $p = .021$). Ability did not have a significant overall effect on normalised mechanical power in males ($ES = 0.31 \pm 0.39$, $p = .170$) or females ($ES = 0.01 \pm 0.62$, $p = .980$). However, between first and third team male singles, there was a non-significant moderate effect ($ES = 0.56 \pm 0.73$, $p = .349$). And in men's doubles, normalised mechanical power in second team matches was greater than first and third team matches ($ES = 0.69 \pm 0.69$, $p = .07$ and $ES = 0.76 \pm 0.67$, $p = .070$, respectively).

Discussion

This study aimed to unobtrusively quantify external mechanical work during badminton match play and identify differences between sexes and disciplines using markerless motion capture technologies. In line with both hypotheses, normalised mechanical work and power were greatest during male and singles match play. Furthermore, the greatest differences between males and females, as well as between singles and doubles, were observed amongst more skilled players. The match play observed in this study was typical of competitive badminton with average rally durations (5.37–6.50 s), rest times (8.69–9.07 s) and shot frequencies (0.80–1.10 per second) akin

to those reported by Phomsoupha and Laffaye (2015). Furthermore, the longer rallies observed in men's singles are in accordance with results from Fernandez-Fernandez et al. (2013).

Normalised mechanical work and power outputs were greater for males than females, confirming that men's matches tend to be more intense (Fernandez-Fernandez et al., 2013). Greater normalised mechanical work outputs during first team men's singles matches can be partly explained by longer rallies and a greater use of mechanically demanding movements, such as lunges (1.01 per point, 95% CI = 0.90–1.25). However, larger mechanical power outputs indicate rallies in these matches were not only longer, but also more intense. Certainly, this can be attributed to males' greater strength (Bishop et al., 1987), aerobic capacities (Tai et al., 2022) and ability to perform fewer unforced errors than females (Abian-Vicen et al., 2013). Similarly, such differences exist between players of higher and lower abilities, regardless of sex (Heller, 2010; Leong & Krasilshchikov, 2016). For these reasons, it is unsurprising that first team males had greater mechanical work and power outputs than females and lower ability males. This, however, fails to explain similarities in results between first and third team females. Like other sports (Gersch, 2021; Runcie, 2019), there exists a sex pay gap in badminton (Kumari, 2022). Consequently, investments into female players are typically lesser, resulting in discrepancies in available opportunities and player development between sexes. Perhaps, it is possible that smaller differences in normalised mechanical work and power between first and third team females arise because of a smaller difference in ability, a product of these discrepancies. Alternatively, it could be that the differences between playing levels on the female side can be attributed to more technical and tactical factors, and playing level is less determined by physical ability. Thus, before any potential changes in the physical capacity within the women's game, female players and their coaches should perhaps prioritise the technical and tactical aspects of their game in order to progress in the sport of badminton.

As hypothesised, normalised mechanical work and power were greater in singles than doubles, reflecting the greater court coverage and more time spent actively playing return shots in singles vs. doubles (Liddle et al., 1996). In males, differences in normalised mechanical work and power between singles and doubles were greater at higher abilities. Indeed, the greater importance of movement in singles is evidenced by singles players' superior agility and speed compared to doubles players (Ooi et al., 2009). Therefore, skilled doubles players may require less movement for success, explaining why there was little change in mechanical work and power across abilities. Furthermore, in this study, the range of abilities in doubles matches was usually greater than in singles matches. Players often adapt their playstyle depending on opposition competency (Macquet & Fleurance, 2007). Therefore, it is possible that by introducing players of lower abilities, skilled players adjusted their performance and reduced their movement as a result, whereas the lower skilled players are likely to exhibit higher mechanical work, which should be accounted for in the prescription of recovery and training practices.

It is important to address the high normalised mechanical work and power outputs observed during second team men's doubles. Though doubles matches are on average less demanding, they can vary more in intensity across matches than singles (Alcock & Cable, 2009). Additionally, it is not uncommon for one player in men's doubles to do significantly more mechanical work than their teammate (Le Mansec et al., 2023). These considerations, coupled with the small sample size in this group ($n = 1$ match), provide a possible explanation for the large results reported. Whilst these cannot be confirmed to be the cause of this result, large variation in the physical demands of match play would have serious implications for training and recovery. Specifically, it would highlight the importance of adaptable training programmes to account for these unexpected quantities of mechanical work and therefore training stimuli. Markerless technologies have the potential to allow this information to be collected totally unobtrusively, with no instrumentation placed on the players, and thus this approach appears promising in identifying important differences in the (mechanical) energy expended.

In contrast to normalised mechanical work and power, 'player load' results indicated that external load between singles and doubles was similar. 'player load' equations, such as the one used in this study, often consider changes in acceleration rather than its magnitude (Bredt et al., 2020). This may explain the observed discrepancies in our results and suggests 'player load' may not be suitable for capturing or distinguishing the physical demands of movement or measuring external loads in badminton. However, it is important to consider that 'player loads' in this study (67.1 – 94.9 AU·point⁻¹) were considerably larger than those reported by Wylde et al. (2019) (~ 15 AU·min⁻¹) who derived 'player load' using accelerometers. Such discrepancies in 'player load' results when methodology and equipment are not matched are common (Gomez et al., 2019), making comparisons between the studies difficult and limits the utility of these metrics.

Several considerations regarding the methodology used in this study require addressing. Due to the long saving times of the full HD video from eight cameras, it was not possible to collect data for every point of the match. We did, however, collect 30 points across the entire match and so feel we have captured a representative sample that has allowed the appropriate and robust comparative analyses. Nonetheless, we acknowledge that it is possible that the dynamics of the match were not fully captured. Whilst statistical power was sufficient for comparisons between the main groups of sex and discipline, it may have been too low for the smaller groups of different sex, discipline and ability. It is therefore possible that relationships that would have altered conclusions were not detected. Furthermore, grouping players by team was not able to provide a true measure of player ability and failed to account for differences between individuals within teams themselves. Consequently, some conclusions made in this study may not necessarily translate to other player populations, such as elite professional players. Additionally, whilst markerless technologies are extremely promising and show very good agreement with marker-based technologies for sagittal plane movements, especially when a kinematic model is fitted to the key points (Kanko et al., 2021; Needham et al., 2022), the precision in the minor planes of motion (e.g., ab/adduction) is poorer.

Nonetheless, as we are only investigating the centre of mass movement in the current study (which is weighted sum that will cancel out some errors), it is likely that these subtle differences are less noteworthy. Injury risk is multifactorial and not solely determined by external loads (Rangasamy et al., 2022; Wang et al., 2024). As markerless motion capture becomes more accessible, research should aim to investigate how external loads and other injury risk factors interact to determine injury incidence, as well as linking this external workload to internal responses. By mapping the external work to an athlete's internal fatigue response, players and coaches could understand the individualised recovery that is necessary for players to continue to adapt and progress, rather than regress, and to avoid potentially becoming more susceptible to injury and illness. This knowledge would not only aid in training prescription but may also prove to be key in the development of autonomous injury prediction models (Van Eetvelde et al., 2021). Indeed, the power of machine learning methods in injury prediction is emerging, but if these models are to advance, greater quantities of relevant data are required (Amendolara et al., 2023).

Conclusion

For the first time, external mechanical work was unobtrusively measured during real badminton match play using markerless motion capture technologies. Greater mass-normalised mechanical work and power outputs recorded during higher ability men's singles matches reflect their more physically demanding nature compared with doubles and women's match play, partly due to increased frequency of shots and higher number of decelerative actions (e.g., lunges). These findings emphasise the need for additional strength and conditioning training and appropriate recovery amongst elite badminton players to ensure that physical condition and match play demands are adequately matched. However, injury risk is not solely determined by the external loads experienced by players, and other physical (e.g., strength and fatigue-resistance) and biomechanical (e.g., joint moments and reaction forces) factors must be considered. Alongside regular monitoring of the external mechanical work experienced by players, accounting for these factors could aid the prevention of injury in badminton.

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