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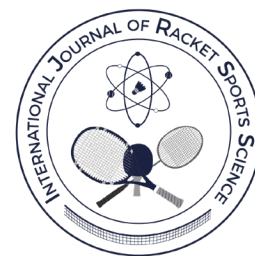
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Editorial

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Many thanks to David Cabello and Adrian Lees for the invitation to contribute to the International Journal of Racket Sport Science both as an associate editor and to offer some editorial thoughts at the time of Issue 5.

My colleagues, Dr David Alder, and Dr Jamie Poolton, and I (all based in the Centre for Sport Coaching, and Carnegie School of Sport, Leeds Beckett University, in the United Kingdom), will offer some thoughts on the racket sports research space, as seen through the articles published in the IJRSS.

David and Jamie offer a perspective from performance analysis, skill acquisition, and expert performance. My perspective is much more about performance development and high-performance systems, culture, and workforce, and notably the role and practices of coaches.

We took this editorial opportunity to review the IJRSS output from the first volume in 2019, to latest volume 5, which covers 2023. There have been 55 articles published excluding editorials – so well done to David Cabello and to the racket sports research community for generating this knowledge, for taking the time to clearly articulate it, and to the editors and peer reviewers for helping researchers to get their articles ‘over the line’.

We attempted to categorise the articles published so far by looking at their titles. This was, we admit, a somewhat crude exercise and we are certain that the researchers and authors whose work we quickly inspected would, in many instances, offer alternative categorisations. Our job here is not to be overly systematic just to offer some higher-level observations, and others may take up the challenge of a more systematic and rigorous review.

We calculate that of the 55 articles, 30 (55% of the total) are concerned with what we have called ‘analysis of performance’. This is understood as the objective examination of sporting performance with the aim to improve future performance attempts. A further 7 explored technology and its application, and 6 had a physiology (with an injury/health) orientation. Most of these 43 articles (78% of the total) offered substantive findings, but some are more methodologically orientated (e.g. how we measure and analyse performance).

There was less publication activity in the discipline of psychology (3 articles), and in systems, workplace, culture, and workforce; for example, performer development systems (2 articles), physical education (2 articles), and coaching (3 articles). There were also 2 articles on racket sport events.

We are not surprised by the balance between sport science (with the exception of psychology in this instance), and systems, workplace, culture and workforce, since this is fairly typical of sport and sport science publication more generally. We have no doubt that the former offers some excellent insight, and we will say more about the analysis of performance shortly.

However, we also ask, in a world where individuals, groups, organisations, and societies are becoming increasingly sensitive to cultural and well-being issues, whether we, as a racket sport research community, should look to focus more on interpersonal, cultural, and workforce issues as we grow? This may well include a broader view of psychology within cultural and behavioural concerns and interests. We note that in the truly international world of racket sports, there may be particular benefit in cultural comparative research between east and west, and the global north and south. This would mean being sensitive to global differences, but also noting societal and sporting change.

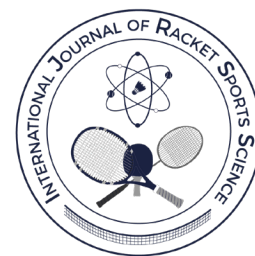
Whilst the practical application of analysis of performance is widespread across many sporting contexts, there is limited research examining best practice examples, principles and ways of working. Most previous efforts have focused on the what (i.e. key performance indicators, technique analysis etc.), whilst little attention has been given to the how (i.e. the integration of performance analysis into player development systems). Despite analysis of performance increasingly being considered as a cornerstone of an ever-evolving coaching process, it is still unclear what the optimal processes are to deliver such support.

We were pleasantly surprised that there were three articles on coaching, but also make the point that much more could be done. Coaches are often the first line of support to athletes, and can be the filter, enabler, but also blocker, of performance analysis and other sport science services and research. We note an ongoing mismatch between the importance of coaching to player development and high performance and the value attached and attention given to it. We would like to see this addressed in racket sports research, and more generally.

Finally, we note an article exploring the role of artificial intelligence in performance analysis. We are aware of other colleagues internationally applying this exciting but also controversial technology. It will be interesting to see how this strand of work evolves, and whether researchers can both maintain a broader gaze and a critical eye on its philosophical, social, and practical implications.

Markov-chain Modelling and Simulative Assessment of the Impact of Selected Tactical Behaviours in Modern Tennis

Modelado mediante cadenas de Markov y evaluación simulada del impacto de determinados comportamientos tácticos en el tenis moderno



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Abstract

Game behaviour in net games or other sports is often captured in the form of discrete performance indicators which represent frequencies or relative frequencies of key behavioural variables. In this regard however, discrete performance indicators are often of low practical relevance as they lack information on the sequence of actions and the underlying interaction of players in a match. Thereby, establishing a connection between performance indicators and sport success also remains an open challenge. In tennis, finite Markov chain modelling based on a transition matrix has shown promise in circumventing these issues. The transition matrix allows the capture of equivalent classes of strokes as a sequence of states with the possibility of transitions between them, basically representing a rally. Furthermore, finite Markov chain modelling enables the determination of the relevance of state transitions regarding performance. Since existing state transition models may be outdated a major aim of the current study was to establish a newly designed transition matrix which is representative of the game structure of tennis. The sufficiency of the transition matrix as a descriptive tool was demonstrated using actual match data. Furthermore, the relevance of selected state transitions was determined using finite Markov chain modelling. Match data and emerging values for performance relevance were analysed with regard to the influencing factors of sex and court surface. This revealed only minor differences regarding both factors, specifically indicating a convergence of game structure in men and women.

Keywords: *finite Markov chain modelling, state transitions modelling, tennis performance indicators, theoretical performance analysis, tactical behaviour.*

Resumen

Los comportamientos durante los juegos de red u otros deportes suelen capturarse en forma de indicadores del rendimiento discretos que representan frecuencias o frecuencias relativas de variables conductuales clave. Sin embargo, en este aspecto, los indicadores del rendimiento discretos suelen tener poca relevancia práctica ya que carecen de información sobre la secuencia de acciones y la interacción subyacente de los jugadores durante un partido. Por lo tanto, establecer una conexión entre los indicadores del rendimiento y el éxito deportivo sigue siendo un reto. En tenis, el modelado mediante cadenas de Markov finitas basado en una matriz de transición se muestra prometedor para sortear estos problemas. La matriz de transición permite capturar clases de equivalencia de golpes como una secuencia de estados con la posibilidad de transiciones entre ellos, representando básicamente un intercambio de golpes. Adicionalmente, el modelado mediante cadenas de Markov finitas permite determinar la relevancia de transiciones de estado con relación al rendimiento. Dado que los modelos de transición de estado actuales pueden estar obsoletos, uno de los objetivos principales de este estudio fue establecer una matriz de transición con un diseño nuevo que fuera representativa de la estructura de un juego

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de tenis. Se pretendía demostrar la suficiencia de la matriz de transición como herramienta descriptiva utilizando datos reales de partidos. Adicionalmente, la relevancia de las transiciones de estado seleccionadas se determinó a través de modelado mediante cadenas de Markov finitas. Los datos de los partidos y los valores emergentes para la relevancia del rendimiento se analizaron en relación con dos factores influyentes: sexo y superficie del campo. Esto reveló solo pequeñas diferencias con respecto a ambos factores, indicando específicamente una convergencia de la estructura de juego en hombres y mujeres.

Palabras clave: *modelado mediante cadenas Markov finitas, modelado de transiciones de estado, indicadores del rendimiento en tenis, análisis teórico del rendimiento, comportamiento táctico.*

INTRODUCTION

Performance analysis or the scientific analysis of sports performances generally has the objective of identifying and understanding factors which are crucial for performance in sports in order to provide information on how to maximize success (McGarry, 2009). In the context of game sports, i.e. invasion games, net games and striking/fielding games (Read & Edwards, 1992), performance is mainly determined by target-oriented behaviors or tactical actions and less dependent on biomechanical and physiological components (Hughes & Bartlett, 2002). In theoretical performance analysis, these tactical behaviors or game behaviors are generally assessed as performance indicators applying the research methods of game observation and notational analysis. Performance indicators reflect aspects which are deemed relevant for performance in a specific sport. Performance indicators mainly represent the frequency or relative frequency of a corresponding behavior (Hughes & Bartlett, 2002). In tennis, performance indicators are mostly presented as success rates of certain key behaviors or game variables. These may include among others, percentages of first serves or returns played in, point winning rates after respective serves and returns, as well as absolute variables like the number of aces and double faults (Ma et al., 2013; Reid, Morgan & Whiteside, 2016).

An alternative method to scrutinize the structure of sports could possibly be found in Markov chain modelling (Lames & McGarry, 2007). Markov chain modelling represents a form of probabilistic modelling, which is applicable in a variety of fields, reaching from social sciences to epidemiology. A recent example for an application in medicine may be found in testing the efficacy of Covid-19 vaccines (Vygen-Bonnet et al., 2021). Markov chain modelling in game sports may circumvent some evident shortcomings of discrete performance indicators (Lames & McGarry, 2007).

With regard to their conceptualization, discrete performance indicators lack context since they constitute summative statistics in the form of mean values derived from an individual performance or a set of performances. This results in the negligence of underlying interactions between teams/players and the

sequence of events. Thus, by the mere assessment of discrete performance indicators it is hardly possible to examine the relation between actions and performance outcomes. Means derived from multiple performances, especially in performance profiles which accumulate different performances of an individual athlete (O'Donoghue, 2013), also suffer from the instability of game behavior (Lames & McGarry, 2007). This was for example demonstrated by McGarry and Franks (1996) who found squash players to exhibit varying shot responses to different opponents.

Finally, discrete performance indicators are commonly correlated to outcome variables like ranking position or winning/losing a match with the aim of explaining the success or the lack of it. However, success of certain tactical behaviors is highly context dependent, therefore establishing a definite causality between discrete performance indicators and outcomes might be misleading without knowing the sequential context of game behavior (Sampaio & Leite, 2013).

Markov chain modelling on the other hand can serve descriptive purposes and may also establish a link between game actions and outcomes. Lames (1991) introduced finite Markov chain modelling based on a transition matrix for tennis. Within the transition matrix (see examples in Tables 1-3), a rally is represented as succession of discrete states which are equivalent classes of strokes. Between different states, transitions are possible and quantified by the observed frequency of the corresponding game action. For instance, the first service error rate is given by the transition probability between the states "First service" and "Second service". In general, a state transition models a player's stroke and the associated outcome which may be a following stroke of the opponent as well as a point or an error of the player. This allows the clear differentiation between states, explaining why state transition modelling is especially convenient for net games. Moreover, individual states or state transitions, like the service error rate mentioned above, can be treated similarly to performance indicators. Aggregating states and transitions in the form of a transition matrix, containing each stroke of a match, results in a super rally. Most importantly, this allows to preserve the sequential context of the single rallies. State transition modelling thus provides a more

comprehensive descriptive alternative to the generic display of performance indicators (Lames, 2020).

Net games were already successfully modelled as finite Markov chains in the literature, demonstrating their additional potential (Lames, 1991; Pfeiffer, Zhang, & Hohmann, 2010; Wang et al., 2020; Wenninger & Lames, 2016). Treating the transition matrix as finite Markov chain allows for further computations (Lames, 1991), which will be introduced below. These computations assume the Markov property. The Markov property denotes the so called “memorylessness” of the process, which means that the transition to a subsequent state is merely dependent on the present state of the process (Lames, 2020). Foremost, one may calculate expected rally length and point winning probability starting from each state. As these variables can be directly observed in the real game, they can be compared to their computed equivalents and thus used for validation purposes. Further, by manipulating selected transition probabilities in the transition matrix it is possible to examine the impact of changes in associated game behaviors by the resulting change in the calculated point winning probability (Lames, 1991). As a consequence, this may be seen as a viable method to establish a relation between game behavior and success including dependencies on sex, surface and playing level.

Besides net games, Markov chains have also been utilized in team sports, though the application in this context is scarce as of today. This is arguably due to difficulties in the implementation of the model, for example with regard to different ball possession times of players or teams, as well as objections against the Markov property in this context (Lames, 2020). Liu and Hohmann (2013), who produced one of few applications in football, used a transition matrix based on a grid of field positions of different players. Further, Lames et al. (1997) demonstrated the possibility of differentiating the impact of individual players on success in volleyball.

Generally, applications of finite Markov chain analyses are scarce and in the case of tennis only rather outdated studies exist e.g. Lames (1991). It can be expected that game structure changed considerably since then, for instance due to developments in material (Miller, 2006). Furthermore, the previous design of states was in part unsatisfactory. Concerning returns, there was no differentiation between such following a first or second serve. This might be regarded as a violation of the Markov property as it is known that rates of successful returns after both differ substantially (Lames, 2020). Furthermore, the serve can arguably be deemed the most important aspect in modern Tennis and has considerable influence on the first strokes after serve and return (O’Donoghue & Brown, 2008), which was not contained in the previous model. Finally, expert opinion suggests that net attacks at present do not have the importance they used to

have in the 90ies. Thus, the previous model with its intensive treatment of net game seems to be outdated in this respect as well.

Taken together, the aim of the current study was to establish and validate a newly designed state transition model for tennis which represents the current game structure. The sufficiency of the resulting transition matrix regarding performance analyses was demonstrated with actual and recent match data from top-level tennis. Moreover, it utilized the transition matrix and finite Markov chain modelling to empirically assess state transitions and their tactical relevance with regard to the influencing factors playing surface and sex in modern tennis.

METHODS AND MATERIALS

Data acquisition and sample

Due to the context of present examination, systematic game observation was chosen as a method of data acquisition using a specifically designed observational system. Individual strokes constituted the unit of observation with the stroke types integrated in the transition matrix as attributes of observation (Lames, 1994, p. 48). The stroke types included are given below. Observer agreement was analyzed by comparing observation data with official data from the Australian and French Open. However, in the present context this is rather trivial as the features which were examined only included the initiation of the rally, rally length, as well as which player scored a point. The resulting agreement is 98.1% (Cohen’s $\kappa = .979$).

The analyzed matches were obtained from the online streaming platform “Eurosport player”. Examination included matches on hard and clay court, specifically the Australian Open 2020 (AO) and French Open 2021 (FO) men’s and women’s single competitions, starting from the quarterfinal. This results in the inclusion of 28 matches, 14 for men and women respectively, with data recorded for each player. Consequently, the sample size of recorded match performances was $n = 56$. In the sample of male players two matches were three set matches, three were four set matches and two were five set matches. In the sample of female players six matches were two set matches and one was a three set match. The analysis included nearly 30,000 shots in total.

The sample was chosen to be representative for elite level competition. Samples of men and women both included at least four players which were placed in the Top 30 of either the ATP or WTA world ranking at the respective point in time. In male players average ranking position was 16, average height was 1.89m and average age was 28. In female players average ranking position was 28, average height was 1.75m and average age was 24. The quarterfinal of G. Muguruza vs. A. Pavlyuchenkova in the women’s singles of the Australian Open had to be excluded due to unavailability on the streaming

platform. The match was therefore replaced by the round of last 32 match of G. Muguruza vs. K. Bertens to retain equal sample size. Procedures performed in the study were in strict accordance with the Declaration of Helsinki as well as with the ethical standards of the Technical University of Munich, Germany. Approval of an Ethics committee was not required.

State transition modelling in tennis

The state transition model for tennis used in this study is given in [Figure 1](#). It contains the states and transitions between them representing the possible match flow in a tennis rally. A transition matrix is derived from this model and shows the empirical transition probabilities between the states for a specific match (see transition matrix in [Fig. 2](#)). Thus, a single state transition can literally be seen as equivalent to the ball travelling between both players and the whole matrix as a representation of the course of all rallies in the match in the sense of a “super-rally” described above.

The modelling process starts with first serve (S1). In the case of service error at the first serve, a second serve (S2) takes place. To omit a possible violation of the Markov property regarding the state return in the previous model, which was pointed out by [Lames \(2020\)](#), discrete states for first (R1) and second serve return (R2) are introduced.

To account for different success rates in the first few strokes of a rally, ([O’Donoghue & Brown, 2008](#)) groundstrokes were differentiated according to stroke numbers associated to the presumed period of advantage/disadvantage for the serving and returning player in the early phase of the rally. Thereby, the state groundstrokes 3/5 (GS 3/5) represents the first two strokes of the serving player after the return and the state groundstrokes 4/6 (GS 4/6) represents the first two strokes of the returning player after the return. The state groundstrokes >6 (GS >6) represents all subsequent strokes where an advantage/disadvantage resulting from the rally opening is no longer assumed.

Presuming a lower frequency of net play, the newly defined state net includes all strokes where at least one of both players is positioned between the service line and the net. Likewise, the state includes attacking groundstrokes where the player clearly aims to approach the net, as well as groundstrokes played in response to one of the former situations. Also, the possibility of a transition from net play to further groundstrokes, e.g. by neutralizing a net attack with a lob and then continuing the rally from base-line is contained in the model.

Besides equivalence classes for specific strokes, the model also allows for the transitions to point and error which evidently represent the end points or absorbing states of the state transition model. The state point includes all winners, whereas the state error includes all strokes played out or in the net.

Finite Markov chain modelling

Besides the descriptive features of the associated transition matrix, finite Markov chain modelling constitutes a form of probabilistic modelling which allows for the calculation of interesting variables with regards to performance analysis. In the case of finite Markov chains, the transition matrix is distinguishable by a limited number of states. Moreover, it features the possibility of transitioning to absorbing states (point and error), which on entry imply the termination of the process in the current modelling step. All assertions made on definitions regarding Markov chains and related calculations in this paragraph are based on the textbook “Finite Markov Chains” by [Kemeny and Snell \(1976\)](#), referring to [Lames \(2020\)](#).

Calculations are based on the empirical transition matrices of both players in a match. Firstly, one may obtain the average frequency with which any state is touched in one step of the process, in this case a rally. From thereon it is likewise possible to calculate the steps until absorption from any state. Taking this value starting with state first serve gives the expected rally length. Other than that, also the absorption probability from any state in either of the absorbing states can be calculated. The absorption probability in state point is equivalent to the respective point winning probability. Here, the point winning probability starting with the first serve is of paramount relevance since this is the overall point winning probability and will subsequently be used to determine the impact of individual state transitions.

For the latter purpose, [Lames \(1991\)](#) introduced a method that allows the determination of the relevance of tactical behaviors or actions through manipulating the associated state transitions, i.e. by simulation. An alteration of the transition probabilities subsequently results in a positive or negative change of the overall point winning probability. The size of the change in winning probability reflects the impact of the simulated behavior and is termed performance relevance.

More concretely, the original transition matrix allows to calculate the overall point winning probability. After this, the performance relevance of a certain tactical behavior is determined by simulating a change in the frequency of the corresponding transition. Subsequently, the point winning probability is calculated again, now for the manipulated matrix. The difference between the point winning probability before and after the simulation denotes the performance relevance (PerfRel) ([Lames, 1991](#)). In the present study, the relevance of winners, errors and selected transitions in different stroke classes were simulated by manipulating the corresponding transition probabilities. Determining the PerfRel using the theory of Markov chains and above-mentioned method presents several conceptual challenges, e.g. modelling the amount of changing a transition to represent a comparable difficulty, the details of which are described in [Lames \(2020\)](#).

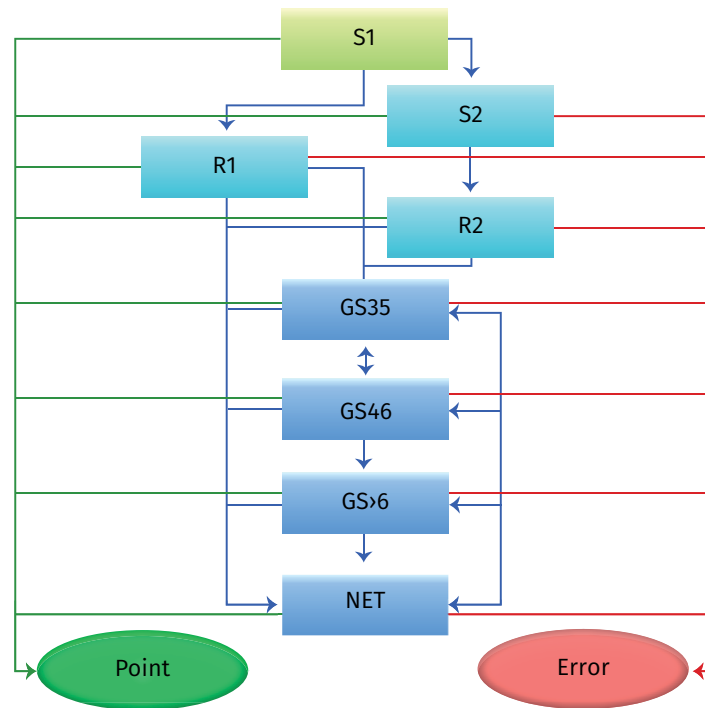


Figure 1. State transition model with possible state transitions.

Legend: **S1:** 1st Serve. **S2:** 2nd Serve. **R1:** 1st Serve Return. **R2:** 2nd Serve Return. **GS35:** Groundstrokes #3 & #5. **GS46:** Groundstrokes #4 & #6. **GS>6:** Groundstrokes > #6

The adherence to the Markov property is the prerequisite for all computations involving Markov chain modelling (Lames, 2020). It may be tested by comparing the calculated model values for rally length and point winning probability to the corresponding real-world values, which can be obtained by game observation. Here the underlying premise is that if both values exhibit satisfying concurrency the violations of Markov property can be assumed to be negligible. Further, this also evidences general model validity. We obtained a correlation of $r = 0.946$ between the observed winning probabilities ($n = 56$) and the predicted ones based on our state-transition model, assuming the Markov property. This can be deemed very sufficient even when applying strict standards. This also holds true for the concurrency of predicted and observed overall rally length with a correlation coefficient of $r = 0.962$.

Statistical testing

To examine discrepancies in tactical behavior and game structure regarding the factors sex and court surface transition probabilities and performance relevancies of the same were compared using a multi factorial ANOVA. The impact of court surface was assessed by comparing two tournaments, French Open (clay) and Australian Open (hard court).

Violations of the assumption of normal distributed data, which occurred in a few instances, were neglected, as the respective sample sizes of $n = 56$ for

sex and court surfaces were deemed large enough to allow for the application of ANOVA. Besides, ANOVA is generally robust concerning non-normally distributed data which resembles a Gaussian distribution (Blanca Mena et al., 2017; Bortz & Schuster, 2011, p. 214; Herzog, Francis, & Clarke, 2019, p. 56). Caution has to be exerted, when drawing inferences from variables which showed differences in variance as this might inflate the Type 1 error rate. In our case though, the impact of unequal variances is not severe due to equally sized sample groups (Bortz & Schuster, 2011, p. 214; Herzog et al., 2019, p. 57). The significance level was set to $\alpha = 0.05$.

Post-hoc two-sample t-tests were used to investigate differences regarding sex within both tournaments and court surface within both sex-groups. To account for the problem of multiple comparisons and associated inflation in type 1 error probability, Bonferroni corrections were applied, resulting in an applied significance level of $\alpha = 0.0125$.

State transitions with a particularly low appearance of under $n = 10$ on average per match were excluded from the analysis.

RESULTS

The result section first depicts a transition matrix for one match to demonstrate its capability to give an overall description of the match with strengths and weaknesses of a player relative to his opponent. Then, aggregated transition matrices are shown to provide

something like a general structure of the rally in the sense of theoretical performance analysis (TPA; Lames & McGarry, 2007), for example for men on clay court. Furthermore, differences between game structures of male and female players as well as both tournaments are described. Finally, results on PerfRel are given with additionally testing the impact of tournament and sex.

Match Transition Matrix

A transition matrix of a single match gives the possibility of deconstructing a match as can be seen in Table 1. On the abstraction level of seeing the whole match as a super-rally one may compare corresponding transition probabilities and identify advantages and disadvantages of the players relative to the opponent.

The table below shows the transition matrices of the final of the Australian Open 2020 between Novak Djokovic and Dominic Thiem. Though this match was a contested five-set match (157 to 147 points) some evident differences can be read from the transition sub-matrices which arguably explain the outcome in favor of Djokovic.

Djokovic performed better at the return, exhibiting for example a higher rate of first serve returns with 82.1% compared to 76.9%. This corresponds to a considerably lower R1 error rate (14.7% vs. 19.2%). Second serve returns showed comparable results. Moreover, Djokovic showed lower rates of errors in GS 3/5 (11.5% vs. 14.8%), GS 4/6 (8.6% vs. 10.7%) and very slightly also in GS >6 (12.1% vs. 12.8%) indicating superiority in base line game. On the other hand, Thiem exhibited an advantage at the net evidenced

by a higher point rate (31.3% vs. 17.8%) and lower error rate (16.7% vs. 17.8%) with both players approaching the net in roughly the same frequency. However, this advantage was evidently not sufficient to outweigh Djokovic's superior return and base line game.

Aggregated transition matrices

Tables 2 and 3 display the average transition probabilities of men and women at both tournaments. The aggregated transition matrices allow the examination of differences in the game structure of various sample groups on a descriptive base.

Transitions from R1 to GS 3/5 show a significant effect of sex. Here men showed a lower transition probability to GS 3/5. Likewise, the associated error rate displayed an effect of court surface, which can be attributed mainly to higher error rates at the Australian Open by men. Regarding the state transitions from GS >6, transitions to subsequent GS >6 and errors both exhibited a significant effect of sex in the ANOVA. However, this effect was not present in the post-hoc tests.

Tables 4 and 5 show the descriptive statistics of the state transitions included in the statistical testing. We find only small differences between means and medians meaning that the distributions of the transition probabilities are quite symmetric. A characteristic feature is the large player-to-player variability of the transitions expressed in the span between minimum and maximum values as well as standard deviations. The coefficients of variation (CV%) speak also in favor of high match-to-match variability.

Table 1. Transition matrixes of the male Australian Open final 2020.

Djokovic	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	35.1	58.2						6.7	
S 2			89.4					0.0	10.6
R 1				82.1			3.2	0.0	14.7
R 2				82.5			0.0	3.5	14.0
GS 3/5					79.1		0.7	8.8	11.5
GS 4/6				46.7		34.9	7.9	2.0	8.6
GS >6						80.9	2.7	4.3	12.1
Net				0.0	0.0	4.4	60.0	17.8	17.8
Thiem	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	36.7	56.2						7.1	
S 2			91.9					0.0	8.1
R 1				76.9			3.8	0.0	19.2
R 2				78.6			2.4	0.0	19.0
GS 3/5					77.6		1.5	6.1	14.8
GS 4/6				45.1		34.4	7.4	2.5	10.7
GS >6						81.4	2.3	3.5	12.8
Net				0.0	0.0	0.0	52.1	31.3	16.7

Table 2. Average transition probabilities at the Australian Open.

Men	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	33.0	57.7						9.4	
S 2			91.5					0.7	7.9
R 1				62.0*			8.2	1.1	28.7*
R 2				82.5			2.7	1.1	13.8
GS 3/5					76.1		1.5	7.4	15.0
GS 4/6				45.5		28.2	9.5	2.9	14.0
GS >6						77.8	3.4	4.8	14.0
Net				0.1	0.4	0.6	46.0	32.9	20.0
Women	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	33.8	59.7						6.5	
S 2			90.1					0.0	9.9
R 1				74.3*			3.0	0.5	22.2
R 2				79.9			0.5	3.5	16.1
GS 3/5					74.9		2.6	7.7	14.7
GS 4/6				48.0		28.6	4.1	5.5	13.9
GS >6						75.1	4.0	4.3	16.6
Net				0.0	0.3	3.6	46.9	30.7	18.4

♣: significant effect of sex within the tournament

♦: significant effect of court surface between tournaments

Table 3. Average transition probabilities at the French Open.

Men	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	35.4	59.4						5.3	
S 2			92.0					0.4	7.6
R 1				69.1			9.2	0.8	20.9*
R 2				82.9			1.6	2.4	13.1
GS 3/5					75.2		2.9	7.8	14.0
GS 4/6				47.2		29.7	6.6	2.8	13.7
GS >6						76.5	4.8	4.1*	14.6
Net				0.1	0.0	1.3	54.0	26.4	18.2
Women	S 2	R1	R2	GS 3/5	GS 4/6	GS > 6	Net	Point	Error
S 1	35.7	61.1						3.2	
S 2			85.7					0.7	13.6
R 1				76.1			2.7	1.1	20.1
R 2				78.5			0.3	6.2	15.1
GS 3/5					71.1		2.8	9.6	16.6
GS 4/6				47.7		26.8	4.6	5.2	15.8
GS >6						71.6	2.3	7.7	18.3
Net				0.0	0.5	0.8	40.6	40.5	17.6

♣: significant effect of sex within the tournament

♦: significant effect of court surface between tournaments

Performance relevance

The Figure 2 (above) displays the state transitions, exhibiting the highest values in PerfRel. Therein especially state transitions from groundstrokes to error exhibit high PerfRel, with values of over 1.5% displacement of the winning probability.

The table above shows the PerfRel of all simulated state transitions at the individual tournaments. Additionally significant differences regarding sex

within both tournaments as well as court surface within both sex groups are displayed. Significant differences in the PerfRel of transitions to subsequent strokes occurred in the transition from GS >6 to further GS >6. This can be attributed to the women at the French open which showed higher PerfRel than their male counterparts as well as than women at the Australian Open. Further the PerfRel in the transition from net to net was significantly lower in male players and even more so at the French Open.

Table 4. Descriptive statistics of the state transitions from the Australian Open (AO) included in the testing.

State trans	Mean		Median		Maximum		Minimum		Std Dev		CV	
	M	W	M	W	M	W	M	W	M	W	M	W
S1 to S2	33.0	33.8	34.7	32.3	43.8	46.3	18.9	24.4	6.7	7.0	20.3	20.7
S1 to R1	57.7	59.7	57.9	57.8	69.3	74.4	46.3	43.8	6.7	9.8	11.6	16.4
S2 to R2	91.5	90.1	92.0	92.2	96.7	100	83.3	73.3	4.0	8.3	4.4	9.2
R1 to GS 3/5	62.0	74.3	60.5	74.3	82.1	93.5	49.1	57.7	8.9	10.1	14.4	13.6
R1 to error	28.7	22.2	29.3	21.4	39.1	42.3	14.7	6.5	7.4	11.0	25.8	49.5
R2 to GS 3/5	82.5	79.9	81.9	80.9	94.3	93.3	71.4	55.6	6.2	10.0	7.5	12.5
GS 3/5 to GS 4/6	76.1	74.9	77.3	77.1	86.4	84.8	68.5	49.3	5.1	8.9	6.7	11.9
GS 3/5 to error	15.0	14.7	15.5	13.6	20.4	25.4	10.0	5.6	3.2	5.4	21.3	36.7
GS 4/6 to GS 3/5	45.5	48.0	45.9	47.0	50.0	66.7	38.6	40.4	3.3	6.0	7.3	12.5
GS 4/6 to GS >6	28.2	28.6	27.4	30.4	34.9	35.7	22.9	17.0	4.4	5.5	15.6	19.2
GS 4/6 to error	14.0	13.9	14.5	13.2	22.5	23.4	7.9	4.8	3.9	5.8	27.9	41.7
GS >6 to GS >6	77.8	75.1	79.5	76.2	89.0	86.0	66.3	61.4	5.9	6.0	7.6	8.0
GS >6 to error	14.0	16.6	13.1	15.6	23.3	28.9	5.5	9.6	5.2	5.1	37.1	30.7
net to net	46.0	46.9	46.7	42.7	60.0	100	33.3	16.7	8.3	20.2	18.0	43.1

Table 5. Descriptive statistics of the state transitions from the French Open (FO) included in the testing.

State trans	Mean		Median		Maximum		Minimum		Std Dev		CV	
	M	W	M	W	M	W	M	W	M	W	M	W
S1 to S2	35.4	35.7	35.1	33.5	45.2	45.2	30.3	25.4	3.9	5.9	11.02	16.53
S1 to R1	59.4	61.1	59.9	62.7	64.2	73.0	50.0	48.4	3.9	7.1	6.57	11.62
S2 to R2	92.0	85.7	93.1	89.4	100.0	96.3	83.3	72.0	4.4	8.2	4.78	9.57
R1 to GS 3/5	69.1	76.1	66.7	78.8	83.9	88.9	52.4	53.3	9.3	9.3	13.46	12.22
R1 to error	20.9	20.1	19.9	18.1	31.7	46.7	8.9	8.7	7.4	9.1	35.41	45.27
R2 to GS 3/5	82.9	78.5	86.0	76.9	90.0	95.5	64.0	62.5	7.3	9.4	8.81	11.97
GS 3/5 to GS 4/6	75.2	71.1	77.9	71.2	80.2	79.6	59.8	61.8	6.3	5.9	8.38	8.30
GS 3/5 to error	14.0	16.6	13.3	16.6	28.0	24.0	6.4	10.6	5.4	3.5	38.57	21.08
GS 4/6 to GS 3/5	47.2	47.7	47.5	47.9	53.1	52.9	39.2	40.9	3.8	3.5	8.05	7.34
GS 4/6 to GS >6	29.7	26.8	30.5	27.3	35.4	32.2	21.7	17.1	4.0	3.3	13.47	12.31
GS 4/6 to error	13.7	15.8	14.1	14.7	23.2	24.3	8.1	9.1	4.5	4.7	32.85	29.75
GS >6 to GS >6	76.5	71.6	77.9	69.8	81.8	86.7	69.6	58.6	4.0	7.6	5.23	10.61
GS >6 to error	14.6	18.3	15.4	17.9	20.8	34.5	8.1	11.1	3.3	5.9	22.60	32.24
net to net	54.0	40.6	51.6	42.9	71.2	78.9	41.2	0.0	8.0	20.6	14.81	50.74

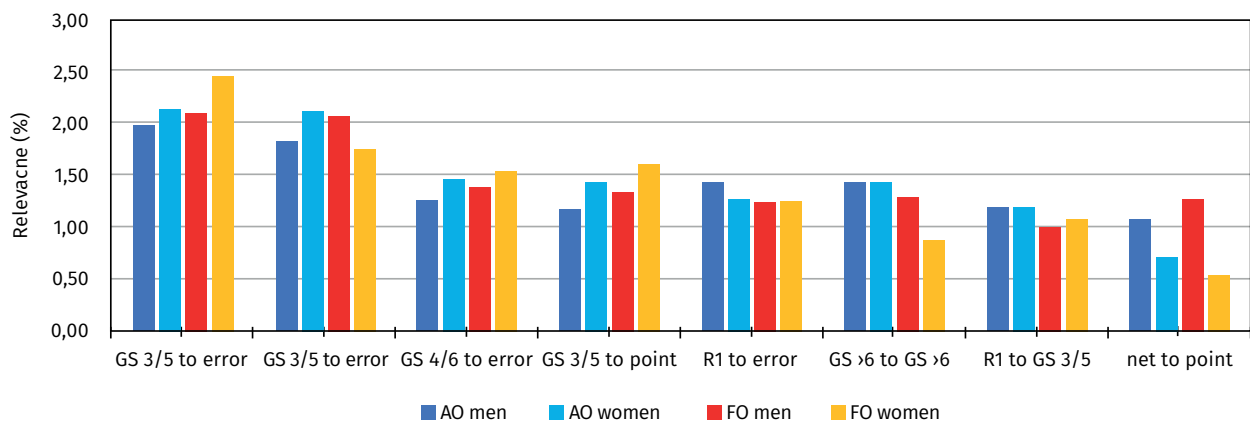


Figure 2. State Transitions with Highest Performance Relevance.

Table 6. Average performance relevance of state transitions with associated group differences.

State Transitions	Australian Open		French Open		Group Dif.
	M	W	M	W	
S1 to R1	0.03	0.16	0.13	0.42	
S2 to R2	0.43	0.50	0.47	0.63	
R1 to GS 3/5	1.18	1.19	0.99	1.08	
R2 to GS 3/5	0.43	0.43	0.38	0.33	
GS 3/5 to GS 4/6	0.94	0.88	0.88	1.03	
GS 4/6 to GS 3/5	0.80	0.74	0.89	0.93	
GS >6 to GS >6	1.08	1.43	1.29	0.87	FO; SW
net to net	-0.28	-0.19	-0.33	-0.17	FO
S1 to point	1.07	0.95	0.83	0.71	-
GS 3/5 to point	1.17	1.42	1.34	1.60	-
GS 4/6 to point	0.64	0.89	0.70	0.86	-
GS >6 to point	0.94	1.00	1.00	0.97	-
net to point	1.07	0.71	1.27	0.54	-
S1 to S2	0.91	0.79	0.66	0.75	
S2 to error	0.46	0.50	0.47	0.62	-
R1 to error	1.43	1.27	1.23	1.24	
R2 to error	0.50	0.59	0.51	0.58	-
GS 3/5 to error	1.98	2.13	2.11	2.44	
GS 4/6 to error	1.25	1.47	1.39	1.54	
GS >6 to error	1.82	2.11	2.07	1.75	
net to error	0.89	0.60	1.07	0.49	-

AO/FO: Significant effect of sex at Australian or French Open
SM/SW: Significant effect of court surface in men or women
- : excluded from testing

DISCUSSION

Transition probabilities

One primary aim of this study was to assess game behavior and the game structure of tennis with regards to the factors sex and court surface using the transition matrix and transition probabilities incorporated therein. In the context of this analysis differences in tactical behavior regarding the factor court surface specifically refer to the difference between hard court and clay court. For this purpose, transition probabilities are compared to related performance indicators from the literature.

The interplay of serve and return seemed to be the main factor of discrepancy regarding sex and court surface in terms of tactical behavior. The associated transition probabilities from R1 to GS 3/5 as well as to error exhibited a significant influence of the factors sex and court surface respectively. Reflected in their lower transition probability to GS 3/5 following R1 male players arguably showed a more dominant and aggressive first serve. This may be attributed to the prevalence of higher serve speed in men which results from their greater physical capabilities. This gives

return players less time to react impeding their ability to stay in the rally and leading to a greater proportion of first serve points (O'Donoghue & Ballantyne, 2004; O'Donoghue & Brown, 2008; Reid et al., 2016). Additionally, the impact of the first serve seemed to be even more profound on hard court. On this surface specifically men exhibited higher rates of first serve return errors than on clay. Thereby, one may conclude a greater impact of first serves on hard court in men. Its lower coefficients of restitution and friction lead to a lower ball bounce and higher ball speeds which make playing a successful return more difficult (Gillet et al., 2009; O'Donoghue & Ingram, 2001).

Present findings therein align with previous examinations which found similar properties regarding the game structure and the associated influence of sex on the first serve and subsequent return (O'Donoghue & Ballantyne, 2004; Reid et al., 2016). However, compared to even earlier findings of Lames (1991) the supposed difference in game structure regarding these factors may be less pronounced. Here significant differences were present in nearly all state transitions associated with first serve and return. Regarding the effect of court surface on the impact of first serves

current examination also reflects previous results. These also indicated a higher impact of first serves on hard court which was for example evidenced by a higher percentage of aces and first serve points at the US Open (O'Donoghue & Ballantyne, 2004; O'Donoghue & Ingram, 2001). It is also important to note, when comparing results to previous examinations that since the 2008 the Australian Open and US Open are played on the same hard-court surface (O'Donoghue & Brown, 2008). Therefore, it is presumably more appropriate to draw comparisons regarding data from the US Open if the examination predates this year.

Regarding the GS 3/5 and 4/6 following the return no differences were present regarding the factors sex and court surface in the examined state transitions. Thus, it can be assumed that tactical behavior regarding those strokes is relatively similar in the current examination thereby contradicting earlier findings. In contrast, O'Donoghue and Brown (2008) found different point winning probabilities in these stages of the rally with regard to the examined factors. This might indicate that in recent years game behavior in male and female players as well as on hard and clay court has become more homogenous. One possible explanation could be found in the progressing development of materials and equipment, which are known to influence stroke parameters (Haake et al., 2007; Miller, 2006). Those may act in favor of game structures converging regarding sex as well as court surface.

Regarding the later stages of the rally results also contradict earlier findings on sex-specific tactical behavior. Generally rallies were assumed to be longer in female players thereby indicating a preference to hold the ball in play instead of going for the point (Lames, 1991; O'Donoghue & Ingram, 2001). In contrast, current examination exhibited transition probabilities from GS >6 to subsequent GS >6 and errors which are quite the opposite of what would have been expected. Female players, on average, showed a higher transition probability from GS >6 to errors and a lower transition probability to further GS >6 than their male counterparts. This could even indicate slightly more offensive tactical behavior in female players in this phase of the rally. Looking at the actual rally length, which was calculated for validation purposes (see section 2.3), it further underpins this presumption with women exhibiting a lower average rally length than male players. Consequently, this may be seen as further evidence for a general change of tactical behavior in women which entails more proactive tactical behavior especially in the form of more offensive groundstrokes.

Yet, aforementioned results must be treated with caution regarding the possible conclusion of women showing more offensive tactical behavior than male players deduced from the significant differences in transition probabilities. Looking at both tournaments individually reveals that aforementioned discrepancies in average transition probability arguably result from the sample of the French Open. However, said

differences were not significant regarding the factor sex when looking at the French Open individually. This is arguably due to the more stringent significance level in the post-hoc test and the overall effect being rather weak. Moreover, at the Australian Open transition probabilities showed almost no difference between men and women for said state transitions, thereby rather pointing in the direction of converging game structures. Additionally, actual rally length at the Australian Open was almost similar between men and women. Therefore, whether tactical behaviors of both sexes just converged or whether women even developed more offensive tactical behavior in this phase of the rally cannot be stated with certainty or may be dependent on court surface. Nevertheless, results likely affirm the hypotheses that game structure and tactical behavior changed considerably over time. Though using a different state transition system, Lames (1991) found more offensive tactical behavior in male players with regards to the rally indicated most notably by their significantly higher prevalence of attacking the net. In contrast current results generally show a low prevalence and importance of net play as well as more similar properties regarding tactical behavior at groundstrokes in both sexes.

Overall serve and return seem to remain the factors which exhibit the greatest discrepancies in tactical behavior between men and women. In subsequent groundstrokes, the game structure of male and female players seems to have been converged indicated by the lack of substantial differences in associated transition probabilities. Compared to previous times, female players seem to exhibit similar degrees of proactive and offensive tactical behavior in groundstrokes than male players. Therefore, it can be argued that overall game structures in men and women have become more homogenous in recent years. Significant differences only emerged with regard to serve and return where the physical advantage of men has the most weight. Furthermore, differences regarding the court surface only emerge regarding serve/return in the examined state transitions. This may likewise indicate a convergence in game structure on clay and hard court.

Finally, the transition matrix and included transition probabilities might also serve practitioners and coaches to derive implications for training as well as helping them in analyzing match performances. Referring to the given match example in 3.1, the transition matrix allows the identify of strengths and weaknesses regarding the frequency of strokes. Herein especially transitions to points and errors may help to identify strong and weak phases in the rally. Also, the transitions between transient states allow to broadly identify certain playing characteristics. For example, the transition to the state net gives implications whether a player shows more defensive tactical behavior in relying on ground strokes or if a player exhibits more offensive tactical behavior in

approaching the net frequently. Further it is also of practical interest to identify where such transitions occur over the course of a rally. A frequent transition from first return to net for example indicates that a player has a proclivity to play serve and volley while the same transition occurring later in the rally could imply that a player shows variable tactical behavior and is good in assessing the right situation to approach the net.

Performance Relevance

The most notable feature of finite Markov Chain modelling in the context of PerfRel is the possibility to link state transitions to performance outcomes. Assertions made regarding PerfRel in this paragraph refer to the percentage displacement of the overall point winning probability resulting from the simulation in the respective state transition. Moreover, an aim of the present examination was to assess the characteristics of PerfRel with regards to the factors sex and court surface.

Generally state transitions to error, especially such from groundstrokes exhibited the greatest PerfRel. Firstly, this is plausible from a conceptual perspective as a change of the error rate is accompanied by an opposite change of strokes played in and point rates. This is especially convenient regarding the error rates in states R1 and GS 4/6, since as a returning player remaining in the rally for longer is associated with increasing point winning probability (O'Donoghue & Brown, 2008). Otherwise in GS 3/5 and >6 changing the error rate is arguably tantamount with changing the frequency of unforced errors. In the state GS 3/5 this can be assumed as the player is arguably in an advantageous position and therefore not forced to commit errors. In GS >6 the rally is likely more evenly matched and therefore presumably often decided by one of the players committing an unforced error. Likewise, both states exhibit the highest absolute frequency of errors besides the first serve presumably contributing to the equally high level of PerfRel. The significantly higher PerfRel of error rates in the states GS 3/5 and 4/6 in female players could reflect a greater reliance on groundstrokes in winning the rally. However, this assertion must be drawn with caution as said effect was limited to the ANOVA and was additionally very small.

S1 and GS 3/5 likewise showed comparatively high PerfRel with regard to the transitions probabilities to point, in men and women. Additionally, the transition from net to point exhibited a high PerfRel in men. The magnitude of the PerfRel in the transition from S1 to point seems plausible, since it reduces the number of errors as well as points played with a second serve and thus lower point winning probability. The relevance of the transition from GS 3/5 might be explained by the frequency of points being highest in this state accompanied by the advantage of the service players

at these strokes. Regarding the PerfRel of the point rate in the state net, it seems that male players rely more heavily on net play than their female counterparts. However, this state transition was omitted from statistical testing as it did not meet the requirement of on average 10 occurrences per match.

Manipulations of the state transitions to subsequent transient states resulted in particularly high PerfRel in the transitions from R1 to GS 3/5 as well as from GS >6 to further GS >6. The PerfRel in the former again is most likely a result of the increasing chance of winning a point for the returning player by keeping the ball in play. The PerfRel regarding the transition from GS >6 to GS >6 may be explained similar to the PerfRel of the error rate in said state. The PerfRel of this transition scaled opposed with regards to sex and court surface. Herein, PerfRel was higher in female players at the Australian Open. In contrast PerfRel of this state transition was higher in male players at the Australian Open, even significantly so. A significant difference in terms of said PerfRel with regard to court surface was only present in women, with female players showing a higher PerfRel on hard court. This could implicate that more offensive behavior in later stages of the rally is convenient in female players on clay court. A possible explanation for this might lie in the slower properties of clay court, which possibly requires female players to take greater risk to win a rally.

Moreover, significant effects of sex were present in both, the transition from S1 to R1, as well as from net to net. The former is arguably more convenient in women as their slower second serve might put them in a disadvantage (O'Donoghue & Brown, 2008). However, the PerfRel of this transition is not paramount in both sexes. Further the transition from the state net to net exhibits negative PerfRel in both sex-groups, since it is obviously disadvantageous to not immediately finish the point when approaching the net. This seems to be even more pronounced in male players, potentially again due to their assumed greater reliance on net points. Overall results regarding sex further substantiate the findings on transition probabilities. Again, the emergence of only minor differences in PerfRel between men and women could indicate the game structures of both becoming more homogenous.

CONCLUSIONS

Establishing a connection between game behavior and sport success is a crucial aspect in identifying key factors for performance in game sports (McGarry, 2009). Here, Markov chains constitute a promising tool especially in the analysis of net games like tennis. Besides, several conceptual challenges remain in the implementation of Markov chain modelling for performance analysis as has been pointed out by Lames (2020).

First, it would be interesting to explore future applications in other game sports. This has been done recently, for example in table tennis by Wang et al. (2020). In invasion games like football, this largely remains an open challenge, with only few applications so far, for example by Liu and Hohmann (2013). The characteristics of such game sports make it hard to establish a meaningful state transition system, for example due to different times of ball possession. One possible solution in this context could be the implementation of continuous Markov chains, as for example demonstrated by Meyer, Forbes, and Clarke (2006) for Australian football. This type of Markov chain uses a continuous time function which could be more suited for the assessment of invasion games.

Further, objections against the Markov property could be addressed by the implementation of higher order Markov chains. A transition to a subsequent state would then not only depend on the present state but could also emphasize several forgoing states. This could be utilized for example considering different winning probabilities following the first few strokes after a first serve in contrast to those following a second serve in tennis, thereby further increasing model quality. Second order Markov chains were used by Wang et al. (2020) in table tennis. Problems with this method are the inflation of the number of states and transitions and the loss of validity of the transitions for tactical behavior, e.g. low frequencies of single transitions, one tactical behavior is expressed in several transitions.

Another problem remains the static display of ratios in the transition matrix. While the transition matrix allows for a general reconstruction of the sequence of events, it still neglects fluctuations of performance over a match. A possible corrective in this matter may be found in the implementation of drifting Markov chains. Those incorporate a polynomial drift to deal with unsteady processes like game actions. This has for example been implemented in the stochastic analysis of DNA-sequences by Vergne (2008).

The present examination arguably also demonstrates the descriptive features of the state transition model as well as the possibility to determine the impact of game behavior through Markov chain modelling. The current examination was thereby able to identify distinct characteristics of the game structure of Tennis in elite level competitions regarding the factors sex and court surface. Therein the main discrepancies occurred with regards to first serve and first serve return. However, the central finding was that the game structure was relatively similar in relation to both factors. Maybe one may give some explanations for that: changes in material which enable women to play faster and accentuate the importance of groundstrokes. Furthermore, women have become more athletic and technically more constant. Thus, passively waiting for an error of

the opponent is not a successful strategy for women anymore as may be perceived in the development of German Angelique Kerber.

Finally, the present examination entails several limitations. First the states in the transition matrix do not or only partially take into consideration information about shot type, playing direction, technique and anthropometrical information of the players included in the sample. However, these factors can be expected to influence states included in the transition matrix, especially the serve. Therefore, the implications drawn from the present examination are limited to the factors emphasized in the transition matrix which are mainly the shot number as well as to some extent the general shot type. Furthermore, while the transition matrix somewhat preserves the sequential context of a rally it still misses the specific context of the underlying individual rallies concerning the dynamic interaction process of players. This also applies to the other mentioned factors, especially playing direction and technique. Therefore, caution must be exerted when drawing conclusions about individual playing characteristics and performances from individual transitions as well as the PerfRel. Furthermore, the sample included in the present examination only allows for drawing conclusions regarding the absolute elite level of Tennis. Therefore, differences regarding the analyzed factors cannot be generalized to a broader population of tennis players.

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European singles and doubles badminton matches analysis with specific focus on pair doubles

Análisis de partidos europeos de bádminton individuales y dobles con especial atención a los dobles por parejas



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Abstract

The main aims of the present study were i) to examine the different demands (temporal and muscular data) between different types of events in badminton (part 1) and ii) to compare the real activity (areas distribution and strokes distribution) between the two players who composed the pair during the three types of doubles that occur in badminton (part 2). Seven matches were analyzed for both men's and women's singles and for men's, women's and mixed doubles during the 2016 European Championships. In Part 1, both timing structure (match duration, number of points, rally duration, rest time, effective playing time and shot frequency) and specific movements (jumps and lunges) were compared between the five types of events. In Part 2, after dividing the court into four zones, we compared the activity of the two players within the same pair in each of these zones. The distribution of technical variables and specific movements was also analysed. For Part 1, male and mixed doubles showed the shortest rally duration (~-45%), the longest rest between two rallies (~+18%), as well as the highest shot frequency (~+24%) when compared to male and female singles and female doubles. Male and female singles showed the highest number of jumps (+40% when compared to doubles) and lunges (+250% when compared to doubles). For Part 2, we observed that spatial and notational distribution between players of the pair is largely dependent on the type of double considered. This study demonstrated that the constraints of a badminton game are specific and related to the type of event played (males or females and/or singles or doubles).

Keywords: *physical demand, smash, racket sports, jump, effort.*

Resumen

Los principales objetivos del presente estudio fueron i) examinar las diferentes demandas (datos temporales y musculares) entre los distintos tipos de eventos en bádminton (Parte 1) y ii) comparar la actividad real (distribución de áreas y distribución de golpes) entre los dos jugadores que componían la pareja durante los tres tipos de dobles que se dan en bádminton (Parte 2). Se analizaron siete partidos de individuales masculinos y femeninos y de dobles masculinos, femeninos y mixtos durante los Campeonatos Europeos de 2016. En la Parte 1, se compararon la estructura temporal (duración del partido, número de puntos, duración del peloteo, tiempo de descanso, tiempo efectivo de juego y frecuencia de golpeo) y los movimientos específicos (saltos y estocadas) entre los cinco tipos de eventos. En la Parte 2, tras dividir la cancha en cuatro zonas, se comparó la actividad de los dos jugadores de una misma pareja en cada una de estas zonas. También se analizó la distribución de las variables técnicas y los movimientos específicos. En la Parte 1, los dobles masculinos y mixtos mostraron la menor duración de peloteo (~-45%), el mayor descanso entre dos peloteos (~+18%),

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y la mayor frecuencia de golpes (~+24 %) en comparación con los individuales masculinos y femeninos y los dobles femeninos. Los individuales masculinos y femeninos mostraron el mayor número de saltos (+40 % en comparación con los dobles) y estocadas (+250 % en comparación con los dobles). En la Parte 2, observamos que la distribución espacial y notacional entre los jugadores de la pareja depende en gran medida del tipo de dobles considerado. Este estudio demostró que las limitaciones de un partido de bádminton son específicas y están relacionadas con el tipo de prueba disputada (masculino, femenino, individuales, dobles).

Palabras clave: *demanda física, remate, deportes de raqueta, salto, esfuerzo.*

INTRODUCTION

During high-level badminton matches, periods of moderate- to high-intensity effort are interspersed with periods of recovery (Abian-Vicen, Castanedo, Abián, & Sampedro, 2013; Phomsoupha, & Laffaye, 2015). This results in a specific temporal structure that coaches should consider when planning training sessions that replicate the demands of a match (Abián, Castanedo, Feng, Sampedro, & Abian-Vicen, 2014; Abián-Vicen et al., 2013; Phomsoupha, & Laffaye, 2015).

Badminton has five types of events, men's and women's singles, men's and women's doubles and mixed doubles. Each of these events requires specific physical and technical skills (Abian-Vicen et al., 2013; Phomsoupha, & Laffaye, 2015). While numerous studies have paid attention to the singles matches (Torres-Luque, Fernández-García, Blanca-Torres, Kondric, & Cabello-Manrique, 2019), the amount of data regarding the doubles is low, especially when women's doubles and mixed doubles are considered (Torres-Luque et al., 2019). The literature classically reported differences in timing structure (e.g. rally duration) and/or physiological (e.g. heart rate) or psychological (e.g. difference personality between single and double athletes) parameters between singles and doubles matches (Alcock & Cable, 2009; Jung Hoon, & Hak-Kyun, 2020; Liddle, Murphy, & Bleakley, 1996; Widyaningsih, Handayani, & Hidayah, 2018). For instance, some studies reported a significant difference in rally duration between singles and doubles, i.e., shorter rallies during doubles than during singles (for the men's doubles and the mixed doubles but not the women's doubles) (Gawin, Beyer, & Seidler, 2015). Nevertheless, there is a consensus on the fact that the speed of the game (shot frequency) is significantly greater during doubles matches (for the men's doubles and mixed doubles but not the women's doubles), highlighting the high intensity during doubles (Alcock & Cable, 2009; Gawin et al., 2015). Authors also highlighted some differences between men and women: women's doubles had longer real times played, effective playing times, rally times, and work densities, whereas men who played in doubles matches showed greater intensity (i.e.,

shot frequency) (Abián-Vicen, Sánchez, & Abián, 2018). Thus, these results suggest that singles and doubles are disciplines that differ in terms of conditional or technical qualities. This is partially supported by the fact that no elite athlete is highly ranked in both singles and doubles at the same time (Torres-Luque et al., 2019).

Surprisingly, no previous study examined if the demand differs between players that play together in a double (i.e. within the pair). This is important as players behave differently on the court: for instance, during an offensive situation, players usually take different positions on the court, i.e. one player (often the same) close to the net and the other on the rear court. This could probably imply physical, technical and tactical discrepancies such as different displacements and different strokes. To the best of our knowledge, only the study of Sobko et al. has tried to rationalize the edification of a pair of young players (Sobko, Zharkova, Vitsko, Zhukov, & Tsapko, 2020). The authors proposed two ways of forming pairs, that are similarity (for men's and women's doubles) and compensation (for mixed doubles). To date, this assumption has not been verified. A better understanding of the real distribution of the tasks within a pair could be relevant in order to adjust the training program for each player.

The main purposes of the present study were (i) to verify the different demands (temporal and muscular data) between different types of events (singles and doubles, men's, women's, and mixed) (= part 1) and (ii) to compare the real activity between the two players who composed the pair during the three types of doubles that occur in badminton, i.e. men's doubles, women's doubles and mixed doubles (= part2).

METHODS

Design and procedures

Seven matches from the 2016 European Badminton Championship (Mouilleron-le-Captif, France) were analyzed for each of the following events: men's singles (MS), women's singles (WS), men's doubles (MD), women's doubles (WD), and mixed doubles (XD). To be

representative of the very high European level of play (Abián-Vicen et al., 2018) and to take into account the significant differences between the group phase and the elimination phase with regard to physiological demands (Chiminazzo, Barreira, Luz, Saraiva, & Cayres, 2018; Torres-Luque et al. 2019), only the matches of the final phases were used in the analysis (quarter-finals, semi-finals, and finals). At the time of the study, players were ranked from 4th-51th (men's singles), 1st-61th (women's singles), 9th-58th (men's doubles), 5th-43rd (women's doubles), and 4th-50th (mixed doubles) of the world ranking.

Analysis

All matches were recorded with a video camera (AHD-H12 VAZ2S, Aiptek®, Willich, Germany). The camera was placed behind one side of a court (8m) on a platform located 5m above the court, allowing us to analyze all the players. The recordings were analyzed with VLC media player software (V3.0.4, VideoLan, Paris, France). Analyses were performed by one experimenter alone, who was an expert badminton specialist.

Part 1

Timing structure analysis

Timing structure analysis data were gathered using a digital stopwatch. The match duration was defined as the time elapsed between the first service and the time at which the last point was awarded. The rally time was considered the time elapsed between the racket-shuttlecock contact during the service and the time at which the shuttlecock touched either the ground (in or out) or the net. The rest duration was defined as the time elapsed between the awarding of the previous rally and the service of the following one. We calculated the effective playing time as the sum of the rally durations expressed in percentage of the total playing time. The total playing time was calculated as the sum of both the rally durations and rest durations. The shot frequency was calculated as the number of shots divided by the effective playing time (shots per second) (Gawin et al., 2015). Reliability of this methodology was proven to be good in a previous study from our research team (Le Mansec, Sève, & Jubeau, 2017).

Specific movements

The number of vertical jumps (when both feet were lifted off the floor) and lunges performed by each player, i.e., two specific movements (Kuntze, Mansfield, & Sellers, 2010; Lin, Blazeovich, Abbiss, Wilkie, & Nosaka, 2023; Phomsoupha, & Laffaye, 2015), were counted. To ensure that the counts of occurrences were unambiguous, each match was viewed four times.

Part 2

To compare the activity between the two players within the pair, it was necessary to assign a role to each player, with respect to their position on the court when they strike the shuttlecock. For all doubles, we decided to label "player A" the player who played the greater number of shuttlecocks in the rear part of the court (e.g. the man was called "player A" and the woman was called "player B" in XD). Based on this, the names "player A" and "player B" remained consistent for all variables. The court was divided into 4 zones: net (the part between the net and the short service line, i.e. 198 cm), front (the part between the short service line and the center of the court, i.e. 198 cm), middle (the part between the center of the court and the long doubles service line, i.e. 198 cm) and rear (the part between the long doubles service line and the base line, i.e., 76 cm) (Figure 1). A stroke was counted in the net zone when at least one foot was located on the line of the short service line or in front of this line. A stroke was counted in the rear when at least one foot was located on the line of the long doubles service line or behind this line or when the player landed on this zone after performing a jump. We also compared the distribution of typical badminton strokes, such as smash, kill and net.

Statistical analysis

Part 1. All data are expressed as the mean \pm SD. After checking for normality (Shapiro-Wilk test), a one-way analysis of variance (ANOVA) was used to test between discipline differences in timing structure data (match duration, number of points, rally time, rest time, effective playing time, shot frequency) and specific movements (number of jumps, number of lunges).

Part 2. All data were normalized and expressed as the mean \pm SD. "Player A" 's values corresponding to the ratio as follow: $((A*100)/(A+B))$. "Player B" 's values corresponding to the ratio as follow: $((B*100)/(A+B))$. After checking for normality (Shapiro-Wilk test), a one-way ANOVA (6 between-subjects factors) was used to test for differences in the distribution in the four zones previously described (net, front, middle and rear) and notational data (number of jumps, lunges, smashes, nets and kills) between each player.

In both parts, the level of significance was set at $p < .05$, and post hoc analyses were performed when appropriate using HSD (honestly significant difference) Tukey correction for multiple comparisons. For the main effects of the ANOVAs, partial eta squared (η_p^2) are reported, with small, moderate and large effects considered for $\eta_p^2 \geq .01$ (ranged from .010 to .069), $\geq .07$ (ranged from .070 to .139) and $\geq .14$, respectively. For the follow-up tests, Cohen effect sizes (d) are reported, with small, moderate, and large effects considered for $d > .2$ (ranged from .2 to .49), $> .5$ (ranged from .5 to .79), and $> .8$, respectively (Cohen, 2013).

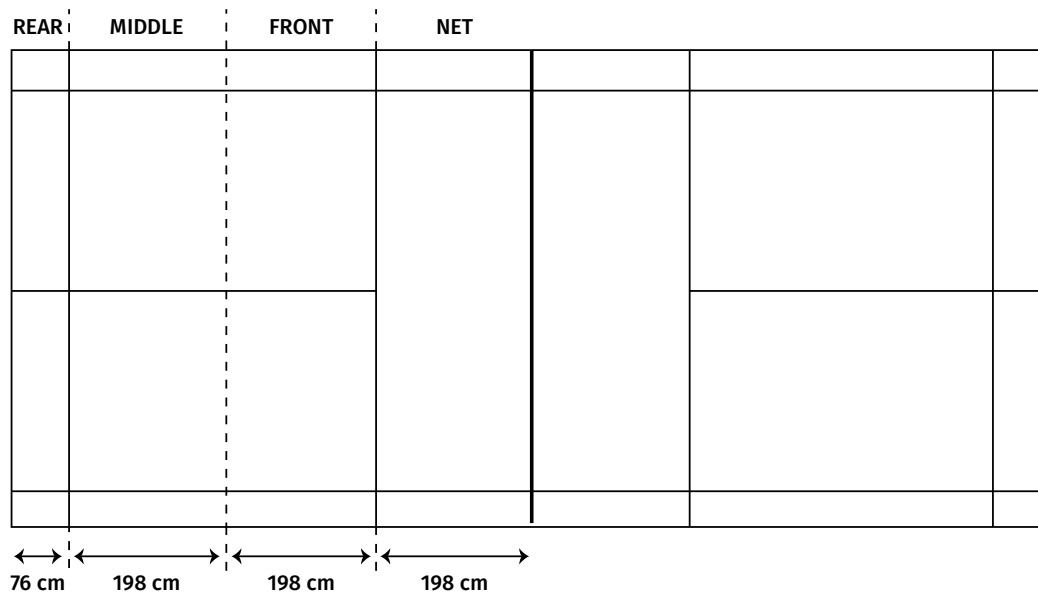


Figure 1. Top view of the four zones (rear, middle, front and net) used to divide the court.

RESULTS

Part 1

Timing structure analysis

All results are shown in Table 1. There was no significant main effect of the group on the duration of the match (average: 42.0 ± 11.6 min). A significant effect of the group was observed for all the other variables (η_p^2 ranged from .345 to .942, $p < .05$)

Rally duration

For rally duration, XD was shorter than MS ($p < .05$, $d = 2.24$) and WD ($p < .05$, $d = 1.60$). MD was shorter than MS ($p < .05$, $d = 2.80$) and WD ($p < .05$, $d = 1.76$).

Rest time

For rest time between two rallies, XD was longer than WD ($p < .05$, $d = 1.92$).

Effective playing time

For the effective playing time, WD was significantly greater than all of the other groups (for all, $p < .05$, d ranged from 2.79 to 5.25). Both XD and MD were significantly lower than both MS and WS ($p < .05$, d ranged from 1.85 to 3.17).

Shot frequency

For shot frequency, WS was significantly lower when compared with all of the groups ($p < .05$, d ranged from 3.91 to 8.86). Both XD and MD were significantly greater than MS and WD ($p < .05$, d ranged from 5.33

to 6.54). MD was significantly greater when compared with XD ($p < .05$, $d = 2.64$).

Specific movements

Jumps and lunges

There was a significant effect of the group on the number of jumps and lunges performed during a match. The number of jumps was significantly greater for MS than XD ($p < .05$, $d = 2.69$) and WD ($p < .05$, 1.59). The number of jumps for WS was significantly greater than XD ($p < .05$, $d = 2.27$). The number of lunges was significantly greater for both MS and WS when compared with all other groups ($p < .05$, d ranged from 2.94 to 3.58).

Part 2

Distribution ("Player A" vs "Player B") depending on the zone

All results are shown in Figure 2 and table 2. A significant effect of the group was observed for the distribution in each zone (η_p^2 ranged from .502 to .680, $p < .001$)

Rear zone

As expected, "Player A" played significantly a greater proportion of shuttlecocks than "Player B" for all types of doubles in the rear zone ($p < .001$, panel A).

Middle zone

"Player A" played significantly a greater proportion of shuttlecocks than "Player B" for both MD and

XD ($p < .001$, panel B) in the middle zone. Moreover, "Player A" played significantly a greater proportion of shuttlecocks during XD than MD ($p < .01$, $d = 1.463$) and WD ($p < .01$, $d = 2.300$).

Front zone

"Player A" played significantly a lesser proportion of shuttlecocks than "Player B" for both MD and WD in the front zone ($p < .01$, panel C) while "Player A" played significantly a greater proportion of shuttlecocks than "Player B" for XD ($p < .001$). Moreover, "Player A" played significantly a greater proportion of shuttlecocks during XD than MD ($p < .001$, $d = 3.111$) and WD ($p < .001$, $d = 4.000$).

Net zone

"Player A" played significantly a lesser proportion of shuttlecocks than "Player B" for both MD and WD ($p < .001$, panel D) in the net zone. No difference was found between "Player A" and "Player B" for XD.

Distribution ("Player A" vs "Player B") depending on the type of action

All results are shown in Figure 3 and table 3. Except for kills ($\eta_p^2 = .142$, $p > .05$, panel E), a significant effect of the group was observed for the distribution of all variables (η_p^2 ranged from .400 to .759, $p < .001$).

Jumps

"Player A" performed a greater proportion of jumps than "Player B" for both MD and XD ($p < .01$, panel A). Moreover, "Player A" performed significantly a greater proportion of jumps during XD than MD ($p < .01$, $d = 1.643$) and WD ($p < .01$, $d = 1.972$).

Lunges

"Player A" performed a greater proportion of lunges than "Player B" for XD ($p < .001$, panel B). Moreover, "Player A" performed significantly a greater proportion of lunges during XD when compared to MD ($p < .001$, $d = 2.055$).

Smashes

"Player A" performed a greater proportion of smashes than "Player B" for all types of doubles ($p < .05$ for all doubles, panel C). Moreover, "Player A" performed significantly a greater proportion of smashes during XD than MD ($p < .01$, $d = 1.475$) and WD ($p < .01$, $d = 3.259$).

Nets

"Player A" performed a lesser proportion of nets than "Player B" for both MD and XD ($p < .01$, panel D). No difference was found between "Player A" and "Player B" for WD.

Table 1.

Comparative results of the timing structure of a badminton game for male singles, female singles, male doubles, female doubles and mixed doubles. Data are expressed as mean \pm SD.

	Male Singles	Female Singles	Male Doubles	Female Doubles	Mixed Doubles	p value	η_p^2
Match Duration (min)	43.0 \pm 12.1	41.5 \pm 10.5	40.5 \pm 12.4	40.2 \pm 12.3	44.9 \pm 13.3	0.95	0.023
Number of Points	81.0 \pm 19.1	79.0 \pm 18.9	86.0 \pm 20.5	89.4 \pm 23.7	90.6 \pm 21.7	0.79	0.052
Rally Duration (s)	8.9 \pm 1.0*#	8.4 \pm 1.1	6.1 \pm 1.0	9.7 \pm 2.7***#	6.3 \pm 1.3	< 0.001	0.501
Rest Time (s)	21.0 \pm 1.7	19.7 \pm 3.2	23.5 \pm 4.8	18.7 \pm 3.3#	24.6 \pm 2.8	0.010	0.345
EPT (%)	27.8 \pm 2.0**#####	26.7 \pm 2.7**#####	21.6 \pm 1.9***	35.1 \pm 3.1***###	21.3 \pm 3.1***	< 0.001	0.808
Shot Frequency (shots.s ⁻¹)	1.09 \pm 0.02#####	0.94 \pm 0.04#####	1.45 \pm 0.07	1.11 \pm 0.03***###	1.30 \pm 0.03***	< 0.001	0.942
Number of jumps	71.0 \pm 22.3***#	57.6 \pm 18.1#	45.0 \pm 23.2	41.9 \pm 12.9	26.6 \pm 6.7	< 0.001	0.454
Number of lunges	158.3 \pm 50.4***#####	174.9 \pm 47.9***#####	46.6 \pm 18.4	47.3 \pm 16.8	50.7 \pm 10.7	< 0.001	0.780

*, ** and *** significantly different from Male Doubles ($p < .05$, $p < .01$ and $p < .001$ respectively). #, ## and ### significantly different from Mixed Doubles ($p < .05$, $p < .01$ and $p < .001$ respectively). † and †† significantly different from Female Doubles ($p < .05$ and $p < .001$ respectively). ###, significantly different from Female Singles ($p < .001$). EPT: effective playing time ; η_p^2 = partial eta squared. p values represent the results of the one-way analysis of variance (ANOVA) for each parameter.

Table 2.

Distribution of areas distribution (number of occurrences, absolute values) between players "A" and players "B" for male doubles, female doubles and mixed doubles. Data are expressed as mean \pm SD.

	Male Doubles		Female Doubles		Mixed Doubles		p value	η^2
	Player A	Player B	Player A	Player B	Player A	Player B		
Rear	19.2 \pm 8.9	9.6 \pm 5.5	44.2 \pm 22.8	31.7 \pm 21.4	22.9 \pm 10.1	13.9 \pm 8.6	< 0.001	0.509
Middle	60.8 \pm 16.8	49.0 \pm 20.0	83.9 \pm 32.1	75.9 \pm 32.3	64.1 \pm 20.0	31.6 \pm 14.6**	< 0.001	0.462
Front	66.6 \pm 21.0	75.0 \pm 25.6	66.8 \pm 21.4	73.5 \pm 17.4	80.5 \pm 25.4	57.1 \pm 18.6**	0.006	0.216
Net	38.1 \pm 14.7	49.9 \pm 15.5	38.7 \pm 14.4	41.8 \pm 13.8	36.0 \pm 12.1	53.6 \pm 19.3**	0.001	0.255
TOTAL	184.7 \pm 52.7	183.6 \pm 54.4	233.6 \pm 75.4	222.9 \pm 68.4	203.5 \pm 57.2	156.2 \pm 47.9	< 0.001	0.269

** significantly different from Player "A" in the same doubles ($p < .01$). η^2 = partial eta squared. p values represent the results of the one-way analysis of variance (ANOVA) for each parameter.

Table 3

Distribution of the actions (absolute values) between players "A" and players "B" for male doubles, female doubles and mixed doubles. Data are expressed as mean \pm SD.

	Male Doubles		Female Doubles		Mixed Doubles		p value	η^2
	Player A	Player B	Player A	Player B	Player A	Player B		
Jumps	49.2 \pm 23.7	42.0 \pm 23.9	44.4 \pm 18.3	39.9 \pm 17.2	35.4 \pm 15.1	18.0 \pm 5.6	< 0.001	0.239
Lunges	45.3 \pm 19.3	48.6 \pm 18.2	51.4 \pm 23.6	43.6 \pm 16.4	62.6 \pm 16.6	40.0 \pm 11.6*	0.026	0.147
Smashes	24.6 \pm 10.8	16.5 \pm 8.0	35.5 \pm 20.1	30.4 \pm 19.4	26.9 \pm 10.2	10.1 \pm 4.7*	< 0.001	0.299
Nets	10.6 \pm 3.8	18.3 \pm 8.2*	13.6 \pm 6.2	15.3 \pm 5.3	14.4 \pm 4.5	21.4 \pm 7.5*	< 0.001	0.255
Kills	6.6 \pm 4.5	8.1 \pm 4.2	5.6 \pm 2.7	8.4 \pm 4.5	6.3 \pm 2.6	9.2 \pm 5.1	0.157	0.095

* significantly different from Player "A" in the same doubles ($p < 0.05$). η^2 = partial eta squared. P values represent the results of the one-way analysis of variance (ANOVA) for each parameter.

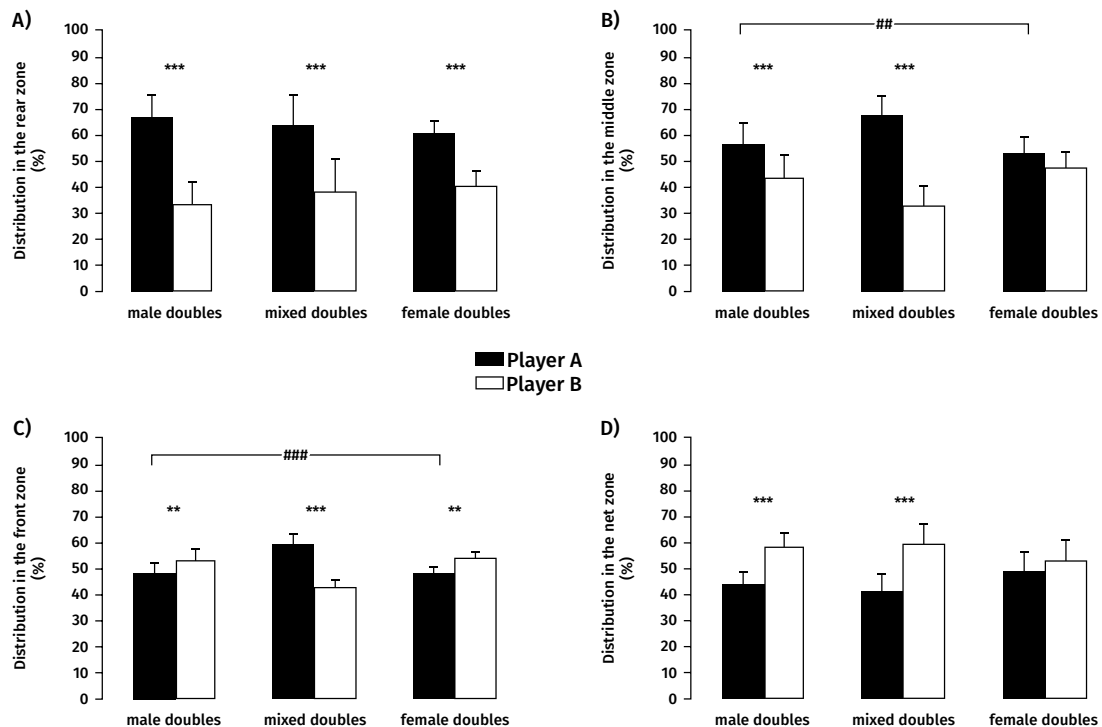


Figure 2. Comparison of the distribution ("Player A" vs "Player B") depending on the zone: rear zone (panel A), middle zone (panel B), front zone (panel C) and net zone (panel D). ** and *** significant difference between "Player A" and "Player B" ($p < .01$ and $p < .001$ respectively). ### and ###, significant difference between the mixed doubles for "Player A" ($p < .01$ and $p < .001$ respectively). Data are presented as means \pm SD. The value of 50% indicates the same distribution between the two players.

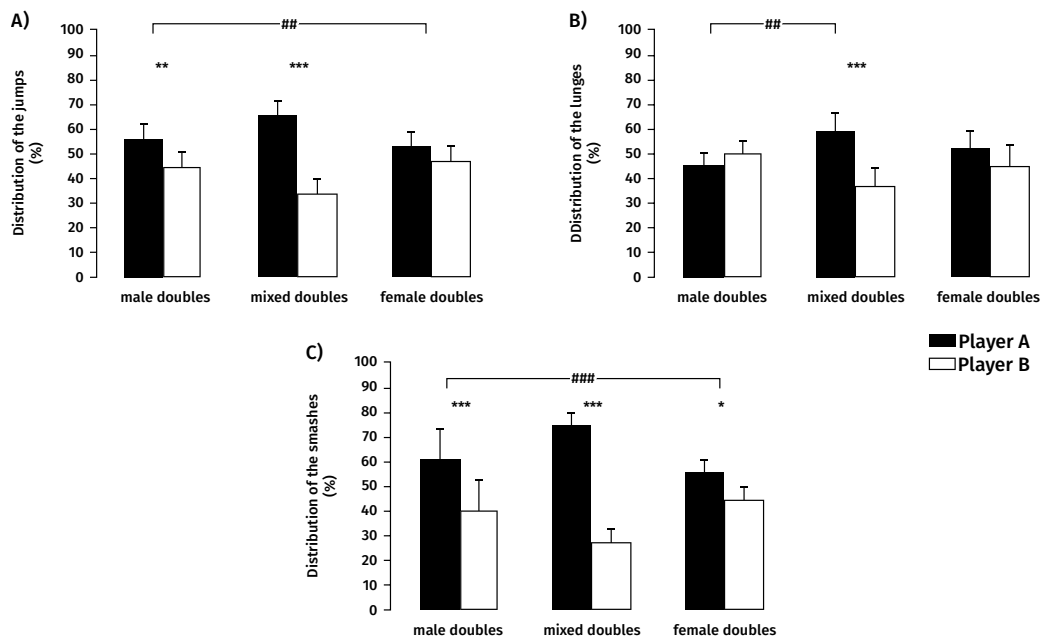


Figure 3. Comparison of the distribution (“Player A” vs “Player B”) for the jumps (panel A), lunges (panel B) and smashes (panel C). *, ** and *** significant difference between “Player A” and “Player B” ($p < .05$, $p < .01$ and $p < .001$ respectively). ### and ####, significant difference between the mixed doubles for “Player A” ($p < .01$ and $p < .001$ respectively). Data are presented as means \pm SD. The value of 50% indicates the same distribution between the two players.

DISCUSSION

The present study showed that the characteristics of doubles games were highly related to the presence or absence of male players. Specifically, we observed that the effective playing time was significantly less during men’s and mixed doubles and the shot frequency was the greatest during these two events. We also found that specific movements, i.e., the number of jumps and number of lunges, were greater during singles play than in doubles play. Furthermore, we found that the activity of the two players performing in the same pair is largely dependent on the type of double considered.

Part 1: Differences between doubles and singles and among different types of doubles

The results of the present study show that the timing structure of a doubles game is largely dependent on the type of doubles. Consequently, the differences between doubles games may vary depending on the presence or absence of a male player in the configuration of the double. Indeed, among the five types of events analyzed, we found that the shortest rallies were observed during men’s and mixed doubles and the longest rallies were observed during women’s doubles. In spite of this, the longest rest time between two rallies was observed during men’s and mixed doubles and the shortest rest time was observed during women’s doubles. However, some results support the idea of specialization between singles and doubles training (Gawin et al., 2015). Indeed, when considered the male players, the effective playing time was significantly greater during men’s singles games than men’s and mixed doubles games. We also observed different muscular demands, i.e. greater jumps (+40%) and lunges (+250%) performed during singles

compared with doubles matches. Thus, the current study confirms the high muscular demand during a singles match (Lin et al., 2023), particularly when compared to a doubles match. Moreover, males aiming to play in doubles matches must be able to develop specific technical skills, such as short serve and return (Gawin, Beyer, Hasse, & Büsch, 2013) and offensive moves (e.g., smash) (Rusdiana et al., 2020), and a great variety of strokes (Alcock, & Cable, 2009), as well as psychological skills to perform under intense mental pressure. As previously observed (Gawin et al., 2015), results are less clear when female players are considered. Indeed, all temporal data show that a women’s doubles game is the most demanding activity involving female players (i.e., in terms of rally duration, rest time, and effective playing time), whereas the characteristics of the mixed doubles game appear to be more similar to the men’s doubles (i.e., low rally duration and a long rest between two rallies). As previously suggested (Gawin et al., 2015), it is likely that the duration of the rally during women’s doubles could be attributable to a lesser speed of the shuttlecock during the offensive strokes, while the defensive skills are equal.

Our results confirm that the shot frequency is greater during doubles games than during singles games (Gawin et al., 2015). Thus, both male and female players wishing to specialize in playing doubles should adapt their training programs by including high shot-frequency sequences to control the technical and psychological constraints of the high-speed game.

Taken as a whole, these results suggest that a high temporal pressure associated with shot frequency requires longer recovery. It could be speculated that greater mental effort is required in double compared to single play.

Part 2: Differences between two players within the same pair.

To the best of our knowledge, the current study was the first to compare the role of the players within the same pair. Sobko et al. study previously proposed two ways of forming pairs depending on the type of doubles, that were similarity for both men's doubles and women's doubles (i.e., identical roles between players) and compensation for mixed doubles (i.e., different roles between players) (Sobko et al., 2020). Our results only partly confirmed this hypothesis.

Distribution related to the space

Men's doubles (MD)

Interestingly, we observed significant differences between the two players in all the zones considered (Fig.2). More precisely, it is noteworthy that the closer from the net, the lesser the "Player A" is involved. As regards the rear zone, "Player A" hits the shuttlecock twice as often as "Player B", while "Player B" hits the shuttlecock 33% more than "Player A" when the shuttlecock is close to the net. This result highlights that the pair actively seeks a preferential position when attacking, thus allowing "Player A" to produce powerful strokes, such as smash, in order to maintain an offensive strategy. This tactical choice has consequences on physical and technical parameters. Thus, "Player A" performed significantly more jumps (+23%) and smashes (+48%) than "Player B" while the opposite has been observed for the net strokes. It has been previously shown that the jump smash is an efficient stroke widely used by the players during doubles matches, requiring several various qualities, such as timing, power and control (Rusdiana et al., 2020). As regards the net stroke, this stroke is usually performed by completing a lunge, which has been thought to be linked to muscular fatigue (Lin et al., 2023). Hence, our results showed that the training programs must take into account the specificity of each player. Contrary to the suggestions of Sobko et al. (2020), it appears that, due to task specificity, compensation principle is more relevant than similarity when re-pairing men's doubles teams.

Women's doubles (WD)

Our results showed a different strategy in WD than that observed during MD. Indeed, although significant difference was observed regarding the rear zone, the distribution between A and B is fairly balanced in all other areas of the court. Thus, it appears that during WD, there is no clearly defined role. The pair relies instead a constant adaptation to the specific situation. This aspect is also visible when comparing the specific movements and strokes. Indeed, no difference was found for any parameter, revealing that the two players have the same tasks. Hence, when compared to men's doubles players, it appears that there is no need to individualize the training programs when

coaching WD, as no specific tasks were found between the two players for both tactical and technical skills. Our results confirm the similarity principle proposed by Sobko et al. (2020) for WD.

Mixed doubles (XD)

As the mixed doubles is the only pair composed by both male and female players, one may expect a different strategy than those observed during MD and WD. Our results confirm this hypothesis by showing that XD is the most unbalanced type of doubles when comparing the spatial distribution of the shuttlecocks played by the players. Thus, "Player A" is largely predominant on the rear half of the court (both the rear and the middle zones). Indeed, "Player A" hits the shuttlecock twice as often as "Player B" in the middle zone. Moreover, the mixed doubles is the only type of doubles in which the "Player A" played significantly more shuttlecocks than his partner in the front zone. Interestingly, "Player A" also played a greater significant distribution of shuttlecocks than "Player B" in the mixed doubles in the central zone, i.e. front and middle zones, when compared to MD and WD. Thus, it appears that during mixed doubles, the female player mainly tries to intercept the shuttlecock in one side of the court close to the net in order to conclude the rally. Consequently, the male player is supposed to cover the rest of the court, included the front zone and sometimes even the net zone. This unbalanced distribution of shuttlecocks is also visible through the actions performed by the players, since the number of jumps, lunges or smashes is largely greater for the male player. The differences of distribution also reach the significance when the "Player A" are compared between XD and MD. Finally, during XD, the female player is predominant to perform decisive actions close to the net, i.e. kills and nets. In the light of these elements, the compensation principle suggested by Sobko et al. (2020) seems to be relevant regarding the mixed doubles.

PRACTICAL APPLICATIONS

Our results strike out highlight reliable skill profiles for training and detection based on muscular and timing structure data. Indeed, while male and female players who aim to play during single competitions must develop both muscular and cardiorespiratory fitness, doubles generally request more explosive qualities. Moreover, as regards men's and mixed doubles players, we also showed that there is a need for individualization training program due to specific roles on the court. For women's doubles players, as the contributions are quite similar, it is important that both players control a large number of technical skills. Consequently, the training program of both players could be identical. Lastly, due to the characteristics of the different events (especially muscular constraints), we also suggested that muscular fatigue is likely to occur during both male and female singles and

doubles. Therefore, coaches and physical trainers should adapt their training programs to counteract the deleterious effects of fatigue (Le Mansec, Perez, Rouault, Doron, & Jubeau, 2020).

LIMITATIONS

Some limitations may be addressed. First, it has to keep in mind that the current study dealt with European players. As the badminton is currently dominated by Asian players, it could be interesting to compare the results observed herein with those observed during Asian and/or world championships. Secondly, as we focused on adult players, future studies are needed to apply the same methodology with young players to detect possible differences. Lastly, to be representative of the European top-level, we chose to analyze only the final phases of the competition. Thus, only seven matches were analyzed for each event. Further studies could confirm the robustness of our results with a large sample of matches.

CONCLUSIONS

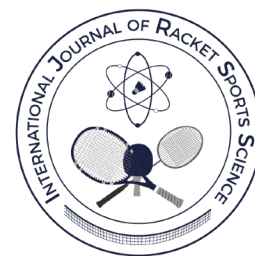
This study demonstrated that the constraints of a badminton game are specific and related to the type of event played. More specifically, our results showed that the characteristics of doubles games were highly related to the presence or absence of male players. This information is highly relevant for coaches and physical trainers to tailor the training programs.

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Factors that contribute to winning medals in international soft tennis events

Factores que contribuyen a la obtención de medallas en eventos internacionales de tenis suave



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Abstract

Soft tennis has four major international events, and to date, 29 official international events have been held. During this period, 576 medals have been awarded. In this study, a two-stage analysis was conducted to explore the factors that contribute to the awarding of medals. Due to the highly skewed distribution of medals, decision tree induction was employed. First, five potential variables were examined for the 10 countries that have experienced medal awards. The results showed that the “Host” effect is not a factor for winning medals, but just a norm of international soft tennis events due to the data bias caused by the extreme concentration of host countries among top four. On the other hand, we found that participation in at least 16 international events is necessary to win a medal. An interesting result for Chinese Taipei (CTP) was found that whether the court surface type is “Hard” or not was a contributing factor for winning more medals. In the second step, we examined the distribution of gold medals for the top four countries which have experienced gold medal awards. The results showed that South Korea (KOR) has won more gold medals on clay courts, and CTP on hard courts than the other courts, respectively. This study determines the effect of court surfaces on winning medals at a national level. It was also found that KOR has won more gold medals at the World Championships and Asian Games than at the other international events. Japan, on the other hand, has won more gold medals at the Asian Championships.

Keywords: *soft tennis, international event, medal winning, decision tree.*

Resumen

El tenis suave tiene cuatro eventos internacionales principales, y hasta la fecha, se han celebrado 29 eventos internacionales oficiales. Durante este periodo, se han concedido 576 medallas. En este estudio se realizó un análisis en dos etapas para explorar los factores que contribuyen a la consecución de medallas. Debido a la distribución altamente sesgada de las medallas, se empleó la inducción de árboles de decisión. En primer lugar, se examinaron cinco variables potenciales para los 10 países que han obtenido medallas. Los resultados mostraron que el efecto “Anfitrión” no es un factor para ganar medallas, sino solo una norma de los eventos internacionales de tenis suave debido al sesgo de los datos causado por la extrema concentración de países anfitriones entre los cuatro primeros. Por otra parte, se constató que es necesario participar al menos 16 veces en eventos internacionales para ganar una medalla. Un resultado interesante para China Taipéi (CTP) fue que el tipo de superficie de la cancha, “dura” o no, era un factor que contribuía a ganar más medallas. En el segundo paso, se examinó la distribución de medallas de oro de los cuatro países que más medallas de oro han ganado. Los resultados mostraron que Corea del Sur

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(KOR) ha ganado más medallas de oro en canchas de arcilla, y CTP en canchas duras que el resto de canchas, respectivamente. Este estudio determina el efecto de la superficie de las canchas en la obtención de medallas a nivel nacional. También se descubrió que KOR ha ganado más medallas de oro en los Campeonatos Mundiales y en los Juegos Asiáticos que en otros eventos internacionales. Japón, por su parte, ha ganado más medallas de oro en los Campeonatos Asiáticos.

Palabras clave: *tenis suave, evento internacional, obtención de medallas, árbol de decisión.*

INTRODUCTION

Soft tennis originated in Japan after the introduction of lawn tennis in the nation. It is a modified version of lawn tennis that developed under the influence of Japanese culture. A few of the characteristic features of soft tennis are as follows: The rackets used are lighter than those used in lawn tennis, the balls are made with a soft membrane of natural rubber, and the doubles game is more popular than the singles game (Ida et al., 2005).

The first international soft tennis event was conducted in 1956 only among Korea (KOR), Chinese Taipei (CTP), and Japan (JPN), even though the game had been played for more than 50 years in KOR, CTP, and JPN by that time (Omote & Japan Soft Tennis Association [JSTA], 1985; 1986). The Japanese introduced soft tennis to the Korean Peninsula in approximately 1905 and to CTP in approximately 1907 (Omote & JSTA).

The first official international soft tennis event, the First Asian Soft Tennis Championship, was held in 1988, with the establishment of the Asian Soft Tennis Federation on February 6, 1988 (JSTA web site, a). After that, international events for soft tennis have been held regularly. There are four major international soft tennis events: the World Championships, Asian Games, East Asian Games, and Asian Championships. To date, 29 international soft tennis events have been held, with a total of 576 medals awarded to the players during these events.

Each soft tennis match consists of a sequence of seven or nine games; hence, the matches are generally played in a shorter amount of time than in tennis. Therefore, most players and coaches believe that the likelihood of uncertainty in the result of a match is very high. Despite a good understanding of the game, no studies have been conducted on factors that determine winning games in international soft tennis events; these events have a greater level of uncertainty regarding match results than do domestic events.

Most sports organizations announce their international rankings periodically on the basis of their original rating systems. For example, the International Tennis Federation, Association of Tennis Professionals, and Women's Tennis Association release the categorized rankings precisely, based

on sex, age, and event. The rankings are calculated on an individual and national basis; however, these rankings only reflect the results. Therefore, players, coaches, and analysts need more useful information to help them win against their opponents.

Bernard and Busse (2004) clarified that the "host" is a better predictor than either the gross domestic product (GDP) or population for winning medals in the Olympic Games. The findings of many other studies were consistent with those of Bernard and Busse and reveal that the host is a strong predictor (Celik & Gius, 2014; Forrest et al., 2010; Hoffmann et al., 2004; Scelles et al., 2020; Vagenas & Vlachokyriakou, 2012), and a "home" advantage exists in the Summer (Balmer et al. 2003; Pettigrew & Reicheb, 2016) and Winter (Balmer et al. 2001) Olympic Games.

In the context of players' performance, home seems to be equivalent to host for encouraging players. Nevill et al. (1997) examined the home advantage effect at the Grand Slam tournaments held in 1993 and reported that players had an effective home advantage only at Wimbledon. However, using four regression models Holder and Nevill (1997), reported little evidence of a home advantage at Grand Slam tournaments. Koning (2011) used a modified logistic regression model in his study, which revealed that a home advantage exists among male professional tennis players, but not among females. To date, it is not clear whether or not there is a home advantage effect at Grand Slam tennis tournaments.

The type of court surface affects the game patterns (Hughes & Clark, 1995; O'Donoghue & Liddle, 1998) and strategies (Hughes & Franks, 2004) in Grand Slam tennis tournaments. A study by McHalea and Morton (2011) revealed a surface effect among the top-ranking players in the Association of Tennis Professionals tour. However, a study by Corral (2009) did not reveal any conclusive surface effects in Grand Slam tennis tournaments, except in female player competitions on grass courts. As for soft tennis, because the ball differs from that used in tennis, the effects of the court surface for soft tennis players will differ from tennis.

The study by Koning (2011) used data from 2000–2008 for men and from 2007–2008 for women, as far as we know, which is the longest duration of data capturing for any study on racket sports science,

and examined the factors that may contribute to winning. Studies using data captured over long time periods can identify significant factors for winning, considering the rapid development of rackets, strings, and other equipment. Knowledge of factors that can help players win tournaments or international events can change the attitude of coaches toward the players and help evolve coaching methods for training them. However, only a few studies have been conducted investigating the number of medals awarded in racket sports in international events.

Fortunately, there is ample information on medals that have been awarded for international events in soft tennis. We summarized the results of four international events for soft tennis held between 1988 and 2019, citing the results described in the study by Omote and JSTA (1985) and on the website “Soft Tennis Homepage,” administrated by the second author (Tanaka, 2019). These data include the results of both individual and team competitions. Table 1 shows information about

the international soft tennis events held and the court surfaces used that were analyzed in this study. However, no analysis has been performed on these wins yet. But in analyzing the information, several problems can be assumed. Tables 1, 2, and 3 show the information on events, court surface, the results of medal winning, and the times of host experienced. It seems clear that the data is biased, especially in medal distributions and the number of host experiences. However, while the number of medals won is a result of the competitions, the number of host experiences is considered factors for the number of medals won. This means we must keep these in mind and care must be taken in the analysis. Thus, we will conduct two-stage analysis to explore the factors that contribute to the awarding of medals.

Therefore, the purpose of this study was to identify the factors that play a role in winning international events in soft tennis. The analysis was performed carefully, as we analyzed potentially biased data.

Table 1

Information about the international soft tennis events held and court surfaces used between 1988 and 2019.

	Events				Court surfaces		
	World Championships	Asian Games	East Asian Games	Asian Championships	Hard	Clay	Synthetic grass
Number of times	8	8	5	8	17	8	4

Table 2

Summary of the results of medal winning races in international soft tennis events.

Country	Gold	Silver	Bronze	Medal tally	Medal winning rate (%)
South Korea (KOR)	75	59	69	203	35.2
Japan (JPN)	54	49	66	169	29.3
Chinese Taipei (CTP)	23	31	64	118	20.5
China (CHN)	3	9	36	48	8.1
Indonesia (INA)	0	4	10	14	2.4
Philippines (PHL)	0	1	12	13	2.3
Thailand (THA)	0	1	5	6	1.0
North Korea (PRK)	0	1	1	2	0.3
Kazakhstan (KAZ)	0	1	0	1	0.2
Mongolia (MNG)	0	0	2	2	0.3

Table 3

Information about host experienced times for the countries and regions.

Events	Countries	KOR	CTP	JPN	CHN	THA	INA	Other countries or regions	
World Championships		3	1	2	1	0	0	1	
Asian Games		2	0	1	2	1	1	1	
East Asian Games		1	0	1	2			1	
Asian Championships		1	1	3	0	2	1	0	
total		7	2	7	5	3	2	3	29

METHODS 1

Despite a history of medal races at international soft tennis events, there has been no investigation into them. Due to the low number of studies on soft tennis, we have little information about the factors that play a role in winning medals at international events. The data that we have include information on events, court surfaces, number of medals awarded to players, number of times a country hosted an event (Tables 1, 2, and 3), and number of international events attended (NIEA). Hence, it is inadequate to assume the factors that play a role in winning medals. Therefore, we need to employ an exploratory approach toward analyzing data, by outlining it first.

We propose that decision tree induction should be employed to obtain insights into soft tennis. A data mining technique can extract useful and previously unknown information from archived data (Ofoghi et al., 2013). Decision trees can also be used on datasets with missing values (Loh, 2008; Morgan et al., 2013). It is a non-linear technique and independent of selection of a prior data distribution (Kawabata, 2008). In addition, the results of decision tree induction can be expressed as a dendrogram, which could help coaches and analysts to interpret the relationships among variables. Further, this technique has the advantages of greater interpretability (Hastie et al., 2009) and the ability to provide greater insights into factors influencing results than linear methods (Written & Frank, 2005). Decision trees have also been used for sports studies such as curling (Willoughby & Kostuk, 2005), participation in daily physical activity, sports of children with disabilities (Ross et al., 2021), food prediction during endurance sport competitions (Fister et al., 2014), match quarter outcome in elite women's Australian rules football (Cust, 2019), and attacker-defender interactions in hockey (Morgan, 2013).

We applied decision tree induction for data analysis of the unbalanced provision of medals in soft tennis. The analysis was done carefully to avoid overfitting. We applied 10 times 10-fold cross-validation (Written & Frank, 2005). This procedure is reliable enough to produce an error estimate for most datasets. Further, we are trying to reconsider the "host" effect, as we do not have enough insight into the host effect yet. Therefore, we must compare the results with and without the host effect. Here we will define the host effect as equivalent to home advantage, because host and home are considered similar in the sense that they encourage to the player (see Figure 1).

All raw medal distribution data were collated and analyzed using JMP 14.3 (SAS Institute Inc., North Carolina, USA). The aim of using the decision tree here was to comprehend the features of the data and identify the possible candidates of variables for subsequent analyses.

Variables

Considering the features of soft tennis and its international events, we investigated five potential factors, described below:

- 1. Court surface:** The coefficient of friction between the ball and the court surface varies depending on the material that the ball is made of (Cross, 2002b; Inaba et al., 2017). In addition, balls deform upon collision with a surface, increasing the area of collision (Cross, 2002a). In the case of soft tennis, rubber hollow balls easily deform upon collision, implying that there are more significant surface effects than there are in tennis.
- 2. Event:** Although soft tennis has four major international events, the values and motivations of players depend on the scale of the event. One major motivational factor is the monetary reward for winning the World Championships or Asian Games in CTP (Chinese Taipei National Sports Medal and Scholarship Award, 2015), CHN (Tan & Houlihan, 2012), and KOR (Takahashi & Kiku, 2013). Further, players are virtually exempted from military service in KOR (Takahashi & Kiku). Therefore, these differences among the events influence players' motivations and performance.
- 3. Country:** Soft tennis has been played for a longer period of time in KOR, CTP, and JPN than in other countries. Hence, it is natural for players from these countries to have a greater advantage in winning medals.
- 4. Host:** Soft tennis is not an Olympic event. Although the Asian Games and the East Asian Games are not major competitions like the Olympics are, they are multi-sport events, and athletes must be registered with and sent by their respective national Olympic committees. The number of medals won by athletes is officially added to their national tally. Therefore, the trends followed at these events are similar to those followed at the Olympic Games. A home advantage is known to exist in individual sports, such as alpine skiing (Martin Gschwend & Alex Krumer, 2021), speed skating (Koning, 2005), boxing (Balmer, Nevill & Lane, 2005), and tennis (Koning, 2011). We believe that the host effect will also exist in soft tennis.
- 5. Number of international events attended (NIEA):** Bernard and Busse (2004) also clarified that the effect of the medal share rate from previous Olympic events is a more efficient predictor than GDP and population. Medal share is expressed as a percentage of the population or GDP, since medal share relative to GDP or population is common in medal acquisition studies on the Olympics. Hence, Bernard and Busse argued that Olympic athletes are similar to durable capital goods that can give several good performances over a long period of time. Their argument indicates that athletes who attend a greater number of Olympic events have more experience; this is applicable to athletes of most sports. It is important for players to build their career with continued participation and by winning performances at international events. This is also applicable to sports organizations.

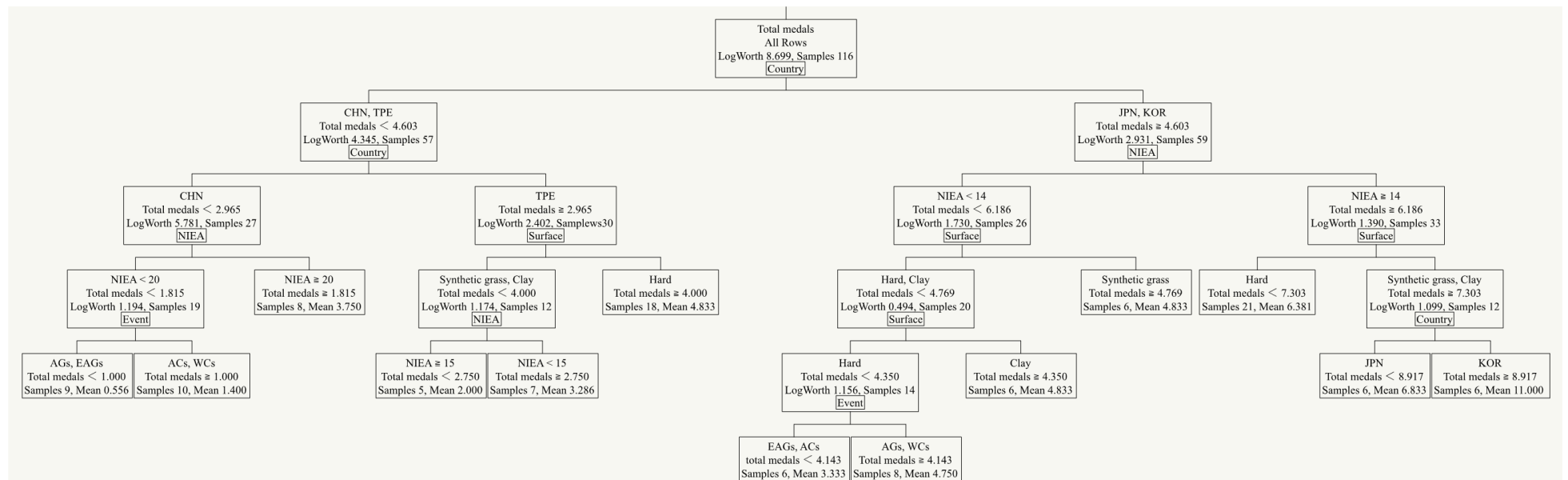


Figure 1. An example of the decision tree nodes for total medals among the top four countries.

RESULTS AND DISCUSSION 1

Our first goal in the exploratory analysis is to determine whether host effects exist. The first split in our decision tree model was caused by the attribute “Country” and the “Host” for total medals won and gold medals won were observed only for KOR, JPN and CTP, and only for KOR and JPN, respectively.

Table 4 shows the results of 10 times 10-fold cross-validation analyses for (i) 10 countries and (ii) the top four countries (KOR, JPN, CTP, and China (CHN)). Table 5 presents the results of the confusion matrices showing the relationships between the host effect and total medals obtained, and the accuracy of our model and recall on host effect. Considering the host effect, the root mean square error and coefficient of determination (R^2) values were close with or without the host in our model (Table 4). Confusion matrices indicated high accuracy to distinguish; however, recall values for both the ten countries and top four countries were very low (Table 5). Considering these results, the host was not deemed to be a factor for winning medals, but is a norm for international soft tennis events due to the data bias caused by exclusive host concentration (that is, the phenomenon that only certain countries are hosts. Table 3). Therefore, “Host” is excluded here for the subsequent analysis.

Table 4
Mean (\pm standard deviation) of root mean square error (RMSE) and coefficient of determination (R^2) on the results of 10 times 10-fold cross-validation analyses by decision tree inductions for the ten and top four countries.

ten countries				top four countries			
with host		without host		with host		without host	
RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
1.407 \pm 0.0187	0.798 \pm 0.005	1.487 \pm 0.0391	0.774 \pm 0.0120	1.809 \pm 0.0149	0.657 \pm 0.006	1.951 \pm 0.0562	0.601 \pm 0.0233

Table 5
Confusion matrices showing the relationships between “Host” effect and total medals obtained, and accuracy of our model and recall on host effect.

	ten countries			top four countries		
	actual	predicted		actual	predicted	
confusion matrix	yes	6	20	yes	6	15
	no	3	200	no	3	92
	accuracy	0.900		0.845		
recall	0.231		0.286			

The results of our decision tree model showed two interesting outcomes for winning medals. For CTP, the court surface type, namely whether the court surface is “Hard” or not, was the contributing factor for winning more medals. In terms of winning medals, NIEA was a significant predictor for every country that attended international events more than 16 times. The attribute “Event” here did not indicate any effects.

This phenomenon implies the need to give systematic support to other countries via the International Soft Tennis Federation, which could yield more participants.

As a whole, all the attributes analyzed, except for “Event” and “Host”, seemed to be good predictors. However, “Event” was a significant predictor for KOR and JPN, who collectively occupy 64.5% of the medal tally. “Event” is likely to be the key for success at international events in soft tennis. Therefore, the exclusion of “Event” is inadequate here. Hence, the remaining three attributes (Court surface, Country, and NIEA) also have been applied to the subsequent analysis.

METHODS 2

As collectively KOR, JPN, CTP, and CHN have won 93.2% of the awarded medals, analyzing the top four countries would make the de facto medal race analysis simpler. The aims of this section were to clarify the factors for winning medals in international soft tennis events more clearly and also to determine the factors that play a role in winning gold medals by analyzing the data of the top four countries that have won gold medals.

Considering the information provided in the RESULTS and DISCUSSION1 section, we proceeded more carefully with the analysis to avoid overfitting. In METHODS 2, we applied 10 times 10-fold cross-validation (Written & Frank, 2005) again.

RESULTS AND DISCUSSION 2

Figures 1 and 2 show examples of our decision tree model for total medals and total gold medals, respectively, among the top four countries. The first split in the model occurred when the attribute “Country” for KOR and JPN was equal to or greater than 4.603 for total medals. Considering the left side of the tree, as well as the RESULTS and DISCUSSION1 section, it is clear that CTP is winning more medals on hard courts, and during the 29 international competitions China has recorded better results in the last decade than in the last three decades. At the right side of the tree, the NIEA seems to be a good predictor for winning medals, but this was the result of an increased number of individual games played in international soft tennis events. Until 1991, only team and doubles events were played. Singles and mixed doubles were first played in 1992 and 2002, respectively. As those results, the number of total medals increased for KOR and JPN.

Considering the left side of the tree in Figure 2, CTP has an advantage for winning gold medals on hard courts. Based on the right side of the tree, KOR has won more gold medals in the Asian Games and World Championships than in the Asian Championships and East Asian Games. This is possibly owing to the social structure in KOR. Players are given monetary rewards and virtually exempted from military service in KOR upon winning gold medals at the Asian Games and World Championships (Takahashi & Kiku, 2013).

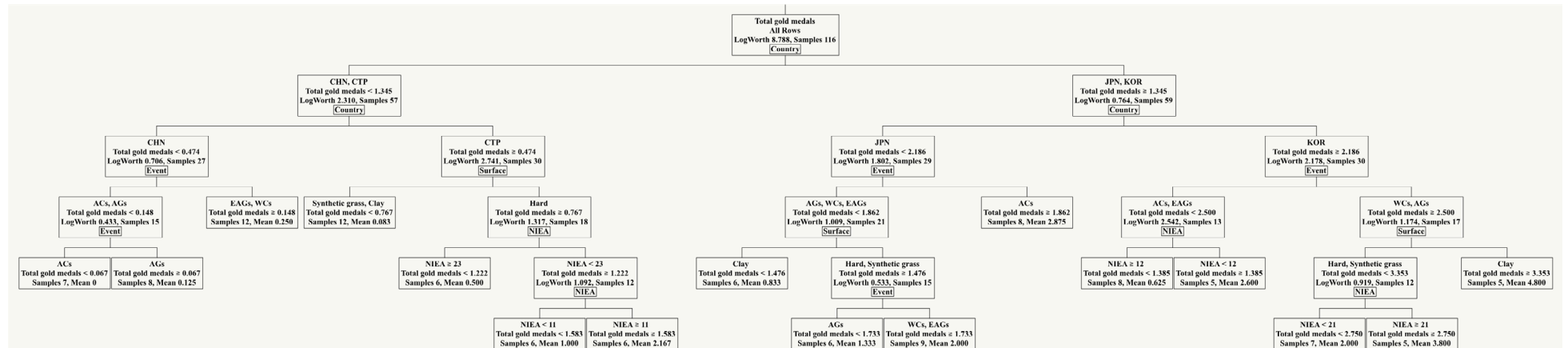


Figure 2. An example of the decision tree nodes for total gold medals among the top four countries.

Further, CTP has an advantage on hard courts, whereas KOR has an advantage on clay courts. On the other hand, JPN has won more gold medals at the Asian Championships than at other events.

GENERAL DISCUSSION

We analyzed the results of the medal winning games of 29 international events in soft tennis held from 1988 to 2019 by using decision tree induction. At first, we analyzed the results of ten countries that had won medals at international events.

The results of the analysis revealed that the chances of winning medals are greater when a country participates in a minimum of 16 international events. For players in other countries, it is difficult to beat players from the top four countries due to the lack of equipment and the difficulties associated with it to hold domestic tournaments (Philippine Soft Tennis Association, personal communication on a certificate of gratitude to Seiji Kusubori on the donation of used rackets. June 5, 2005). Consequently, it will be difficult to gain playing experience in those countries. Even for Chinese players, participation experience in more than 20 events is needed to win gold medals. The argument by [Bernard and Busse \(2004\)](#) on Olympic athletes suggests that players who participate in the Olympic Games several times have more chances to grow in experience, and this is also applicable to other sports organizations. Hence, it is essential for all nations to attend international events continuously each year.

Especially for Southeast Asian countries, it is essential to achieve good results in the Southeast Asian Games to be permitted to attend the Asian Games; the National Olympic Committee can exclude poorly performing nations from participating in the Asian Games (A. L. Tamayo [The president of Philippine Soft Tennis Association] & J. Mamawal [The head coach of Philippine Soft Tennis Team], personal communication, November 13, 2010). Therefore, the International Soft Tennis Federation should support Southeast Asian countries in training and shaping the careers of their players, coaches, and organizations by allowing continuous participation at international events. This may help to reduce the concentration of host country in the top four. The concentration of host country results in unbalanced medal distribution and appears to discourage other national athletes from competing against national athletes from the top four countries.

Another major problem is that the World Championships are held only once every four years. This situation makes it difficult for even highly skilled tennis players to adjust to the differences in equipment, especially the ball (C. Craig [former U.S. national team player and professional tennis coach], personal communication, April 1, 2005). In the European region, several open tournaments have been held as international tournaments (JSTA website,

b). However, these tournaments are only events, and the participating players are always only those from the host country and Asian stars invited for demonstrations. Without systematic and sustained promotion of the sport in regions outside of Asia and support for the participation of players from such regions in international tournaments, it will be difficult to raise the sport's profile as a meaningful international sport. Despite the long history of soft tennis, it seems clear that there has been little progress in promoting and supporting the sport outside of Asia. The reason for this may be that soft tennis is recognized as a mass sport and its diffusion as an international competitive sport has been delayed, as evidenced by the fact that the first international soft tennis tournament in 1956 was held in only three countries: KOR, CTP and JPN ([Omote & JSTA, 1985](#)).

Currently, a World Championship is held only once every four years, but since the East Asian Games ended with the 6th East Asian Games in 2013, soft tennis is now in an environment where a World Championship can be held at least once every two years. In addition, soft tennis has team (national) competition, doubles, singles, and mixed doubles, but it would not be necessary to hold all of these events at every World Championship. Although there is still room for various innovations in holding the World Championships, the current situation remains unchanged, which is another major problem.

Our study revealed an interesting finding based on court surfaces. CTP and KOR have an advantage in winning the most total gold medals on hard and clay courts, respectively. This reflects the geographical factors of CTP and the competition environment in KOR. As CTP players often play on hard courts (K. Koh [former CTP head coach], personal communication, March 31, 2005); therefore, CTP players are more familiar with hard courts. CTP also adopted original playing styles earlier than the other countries, and these are considered reasonable strategies ([Shinohara, 2019](#)). On the other hand, players in KOR usually play on clay courts, and the tennis courts built for the purpose of soft tennis are normally clay courts (H. S. Kim [The managing director of KOR Soft Tennis Association], personal communication, November 14, 2018). We summarized the results of the careers of all tennis players for each court surface using the data from the Ultimate Tennis Statistics ([Table 6](#)). Spanish and South American players seem to have more significant advantages playing on clay courts than on other court surfaces. [Date \(2018\)](#) mentioned that this may be due to a greater ratio of clay courts than other types of courts in such countries.

In tennis, the surface effect for individual players was examined ([Hughes & Clark, 1995](#); [Hughes & Franks, 2004](#); [O'Donoghue & Liddle, 1998](#); [McHalea & Morton, 2011](#)). However, our findings in soft tennis differed for each country. The surfaces used by players during the early period of their career affected their professional

future (Reid et al., 2007; 2009). In addition, Date (2018) argued that the synthetic grass surface courts used widely in JPN prevent the success of their players. This indicates that the success of players depends considerably on their familiarity with the court surface. Fans and coaches often emphasize that South American and Spanish tennis players, especially Rafael Nadal, perform better on clay courts (Date, 2018). Both South America and Spain yield high performance players with powerful records on clay courts (Table 6). However, the records for South American and Spanish players do not have significant differences statistically. Our data show significant differences among the countries. This implies that court surface familiarity is more important for soft tennis than for tennis, as the tennis ball with a soft membrane of natural rubber is easily deformed on collision with the court surface.

Table 6

The numbers of South American and Spanish players who have within Top 50 and 100 lifetime records for three types of courts (clay, glass and hard). South American players are belonging to Argentina, Chile, Brazil, Ecuador and Paraguay.

Types of courts	South American players		Spanish players		South American and Spanish players	
	Top50	Top100	Top50	Top100	Top50	Top100
clay	8	15	8	15	16	30
glass	2	2*	3	5	5	7
hard	4	6	1	5	5	11

Note. No statistical differences existed among types of courts. *No players existed between 50 and 100.

KOR has won gold medals in the Asian Games and World Championships. KOR players have not only won medals at premier events, but are also highly motivated to win gold medals at these events. One of the reasons for these characteristics is that winning a gold medal at such events leads to virtual exemption from military service for KOR players, along with monetary rewards (Takahashi & Kiku, 2013).

Unfortunately, the outcomes for CTP and CHN were not similar to those for KOR. We believe this indicates a need for more detailed analyses on gold medal distributions. On the other hand, JPN has won gold medals in the Asian Championships. In other words, the biggest challenge that JPN faces is finding a strategy by which to win gold medals in the Asian Games and World Championships.

Our findings reflect results at the national level, but do not reflect the background of individual players. There have been cases where players who originally played tennis have competed in international soft tennis events and won medals. Further, our analytical model does not take into account the results of any international events other than the four major events. If the background of individual players and the relationships between the results of the four

major events and those of other international events could be clarified, the path to success at the World Championships and Asian Games could be clarified.

CONCLUSION

The medal distributions of 29 international events in soft tennis held between 1988 and 2019 were skewed toward four countries, KOR, CTP, CHN, and JPN. Due to this unbalanced distribution, a host advantage did not exist in international soft tennis events. Participation in more than 16 international soft tennis events appears to be highly linked to winning medals.

Court surface significantly affected the medal tally for KOR on clay courts and CTP on hard courts. In other words, KOR and CTP have advantages on clay and hard courts, respectively. This study determines the effect of court surfaces on winning medals at a national level; this has not yet been reported for other sports.

KOR has won more gold medals in the Asian Games and World Championships than any other country.

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CONFLICT OF INTERESTS

The authors have declared there is not any potential conflict of interests concerning this article.

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Detection of similarities and differences within the same shot movement using artificial intelligence-based performance analysis: An example of a tennis service

Detección de similitudes y diferencias dentro de un mismo movimiento de golpeo mediante un análisis del rendimiento basado en inteligencia artificial: ejemplo del servicio en tenis



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Abstract

Artificial intelligence (AI) -based performance analysis has the potential to support feedback in coaching; however, a useful method has not yet been proposed. This study aims to develop an AI-based performance analysis to support tennis coaching. Specifically, we investigate the accuracy of detecting similarities and differences within the same shot movement. The participants were two tennis players with more than ten years of tennis experience at the regional level. This study targeted service in tennis and videos of the 1st and 2nd service from both sides (number of services: 40 attempts) were recorded using a smartphone located on the fence behind the participant. The analysis code was executed in Python, and the main part involved the use of BlazePose, which estimates the X-, Y-, and Z-coordinates of a human pose. Video clips of 2 s were cut, with a 1 s overlap between each clip, and one of the clips was manually chosen as the standard clip. The clips were compared with the comparison clips, and the difference scores for the total and each body part were automatically calculated. An AI-based analysis was conducted considering 12 conditions combining the 1st and 2nd services from both sides and different players. As a result, a certain accuracy ($\geq 70\%$) was confirmed for detecting overlapping phases between clips. Moreover, manually evaluated body parts that showed different movements by a certified coach corresponded to the top three different parts in the AI-based analysis for 8 of the 12 conditions. The proposed AI-based performance analysis can effectively extract similar or overlapping phases and suggest body parts exhibiting different movements.

Keywords: Performance analysis, motion analysis, artificial intelligence (AI), tennis, service.

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Resumen

El análisis del rendimiento basado en inteligencia artificial (IA) tiene el potencial de apoyar la retroalimentación en el entrenamiento. Sin embargo, aún no se ha propuesto un método útil. El objetivo de este estudio es desarrollar un análisis del rendimiento basado en IA para apoyar el entrenamiento de tenis. En concreto, se investiga la precisión en la detección de similitudes y diferencias dentro de un mismo movimiento de golpeo. Los participantes fueron dos tenistas con más de diez años de experiencia en tenis a nivel regional. Este estudio se centró en el servicio en tenis y se grabaron videos de los dos primeros servicios desde ambos lados de la cancha (número de servicios: 40 intentos) con un teléfono inteligente situado en la valla detrás del participante. El código de análisis se ejecutó en Python, y la parte principal involucró el uso de BlazePose, que estima las coordenadas X, Y y Z de una posición humana. Se cortaron videos de 2 s, con un solapamiento de 1 s entre cada video, y se eligió manualmente uno de ellos como el video estándar. Los videos se compararon con los de comparación y se calcularon automáticamente las puntuaciones de diferencia para el total y para cada parte del cuerpo. Se realizó un análisis basado en IA que consideraba 12 condiciones y combinaba los dos primeros servicios desde ambos lados y de los diferentes jugadores. Como resultado, se confirmó cierta precisión ($\geq 70\%$) en la detección de fases solapadas entre videos. Además, las partes del cuerpo evaluadas manualmente que mostraban movimientos diferentes por un entrenador certificado correspondían con las tres primeras partes diferentes del análisis basado en IA para 8 de las 12 condiciones. El análisis de rendimiento basado en IA propuesto puede extraer eficazmente fases similares o solapadas y sugerir partes del cuerpo que muestran movimientos diferentes.

Palabras clave: *Análisis del rendimiento, análisis del movimiento, inteligencia artificial (IA), tenis, servicio.*

INTRODUCTION

Sports performance analyses using objective information are increasingly being conducted. In tennis, the target of this study, numerical data such as the success rates of various shots and rallies are often used as objective information (O'Donoghue, 2005). However, a performance analysis should adopt qualitative data, such as videos, to obtain detailed information. Qualitative data analysis takes the form of inputting specific events and labels using specialized software. Although this method can be useful for understanding the characteristics of each scene of play, the interpretation of the information obtained can be influenced by the experience and subjectivity of the players and coaches.

A method for automatically analyzing video data was developed based on the object-detection technology of artificial intelligence (AI), such as machine learning and its division deep learning (Brady et al., 2021; Cust et al., 2019). A systematic review stated that machine learning has been increasingly adopted in tennis tracking or analyzing both player and ball movements (Takahashi et al., 2022). More models are expected to feature deep learning owing to the development of better hardware and advantages of achieving more efficient model learning on large data inputs (Cust et al., 2019), which are suitable for racket sports because of the large number of attempted shots and movements. A systematic review of this research field (Cust et al., 2019) summarized inertial motion unit (IMU)-based and vision-based AI-based performance analyses for various sports. Different methods may be appropriate for different types of sports or situations (practice session or match). For example, in tennis, the vision-based method would be more

useful because there is no need to attach devices to the player and there is potential for application in real matches. The systematic review (Cust et al., 2019) has summarized three studies that used vision-based analysis for tennis (Ó Conaire et al., 2010; Shah et al., 2007; Zhu et al., 2006). However, these studies only classified shot types such as service, forehand, or backhand strokes. Following a systematic review (Cust et al., 2019), Cai et al. (2020) conducted a more detailed AI-based analysis on 12 shots in tennis, and confirmed that there was significant confusion within the same shot, such as between the kick service and slice service.

Human pose estimation has significantly advanced. BlazePose, a lightweight convolutional neural network architecture for human pose estimation developed by Google Research (Bazarevsky et al., 2020) might be useful for tennis performance analysis. BlazePose has the ability to estimate the X-, Y-, and Z-coordinates. Therefore, this method is suitable for tennis analysis, which requires depth estimation for body direction or stance during shot movements. To date, shot classification for six-shot movements in cricket (Devanandan et al., 2021) and estimation of multiple joint angles during tennis service (Yoshida et al., 2021) using BlazePose have been reported. Although these studies suggest the application possibilities of BlazePose in racquet sports, an accumulation of study findings is required to support sports coaching. Information on similarities or differences within the same shot is useful in sports coaching; therefore, AI-based analysis is expected to play a supportive role.

This study aimed to develop an AI-based performance analysis for tennis coaching applications. Specifically, we investigate the accuracy of detecting

similarities and differences within the same shot movement.

MATERIAL AND METHODS

Study design and participant

An experimental study was conducted in a tennis court. The tennis court was blue and light blue in color, and the surface was hard. The study participants were two tennis players, who were also the authors of this study. The participants are experienced tennis players with more than ten years of experience at a regional level. The self-reported height and weight of the two players were as follows: 173 cm, 62 kg for Player 1, and 170 cm, 68 kg for Player 2. This study was approved by the Ethics Committee of University of Tsukuba (approval number: Tai 022-80 and Tai 022-80-1).

Data preparation

This study focuses on tennis service as a target for performance analysis. The reason for focusing on service is that the first service points have a large impact on the win or loss of a match for both professional and junior players (Kovalchik & Reid, 2017). Thus, service is considered to have a high priority in improving tennis shot skills. In addition, the service would be a suitable target for the first step of the developed analysis because it can be performed by one player and does not need to consider the inclusion of opponents in the video.

The proposed method required two target videos. The first was a standard video that included one or more attempts at the target shot. A standard video is assumed to include an ideal movement or movement prior to specific training implementation. The second video was used for comparison. The comparison video included multiple attempts of the shot for comparison. In this study, some service videos of the two study participants were recorded, and certain conditions were set to evaluate the developed method (details are described below).

The videos were recorded at 1920 × 1080 pixels and 60 frame per second (fps) using an iPhone (Apple Inc.). The iPhone was located approximately 1.7 m high on the fence 8.5 m behind the participant and was the same for all conditions. The fence was stable, and leaning over did not affect the camera angle.

Development of AI-based performance analysis

This study developed an AI-based performance analysis method that uses tennis videos to automatically detect the differences and similarities within the same shot movement. The analysis was conducted using Google Colaboratory, an online execution environment for Python (<https://www.python.org/>). Target videos were uploaded to Google Drive's cloud storage system and imported into the environment. The programming

code was prototyped by researchers from Information Services International-Dentsu, LTD. The code was modified based on a preliminary study and discussions between the company and university researchers. Subsequently, the video data were gathered and analyzed by university researchers.

An overview of the AI-based performance analysis is shown in Figure 1. We adopted BlazePose (Bazarevsky et al., 2020), which is a lightweight convolutional neural network architecture for human pose estimation, for the main part of the analysis. BlazePose is one of the models in the Mediapipe framework developed by Google that offers customizable machine learning solutions for processing multimodal data. The technology is open source and available to the public. Although BlazePose can estimate the coordinates of 33 body parts, the developed method targeted 13 body parts (nose, shoulders, elbows, wrists, left and right hips, knees, and ankles) that are important for tennis shot movements. The nose was included because its position would be useful for ascertaining the status of neck rotation, extension, and flexion.

The recorded video was converted from the MOV file to a GIF file and analyzed using developed functions, including BlazePose. In addition to the MOV file, the MP4 video format is also applicable for the analysis. In addition to converting to a GIF file, the GIF file was clipped to short-duration clips with an overlapping duration to conduct an analysis targeting the appropriate phase, such as before and after the impact. A phase indicates the entire or partial movement of a shot, whereas the entire phase indicates a shot. In this study, the clipped duration was set to 2 s, with a 1 s overlap between each clip. One of the clips that included the impact of the ball and racket was manually selected as the standard clip. A clip duration of 2 s mostly covered the entire service phase from toss-up to after impact.

These functions transform the skeletal coordinate information while excluding differences in the recording angle (i.e., between deuce and advantage sides) or position of the camera (i.e., this was not applicable to this study because of the same camera position). Specifically, a skeletal part (the left shoulder in this study) was set as the origin of the coordinates, and parallel shifts and rotations of all spatial coordinates were performed with respect to the origin. The skeletal coordinate information extracted by the functions was used to calculate the difference score between the videos.

To calculate the difference scores, the Dynamic Time Warping algorithm (Sakoe & Chiba, 1978; https://tlearn.readthedocs.io/en/stable/user_guide/dtw.html) was used to consider the movement speed. Scores were calculated for each body part, with lower scores indicating smaller differences between the standard and comparison clips. The average of all body part scores was considered the total difference score for movement in this study. The scores ranged from zero to no upper limit.

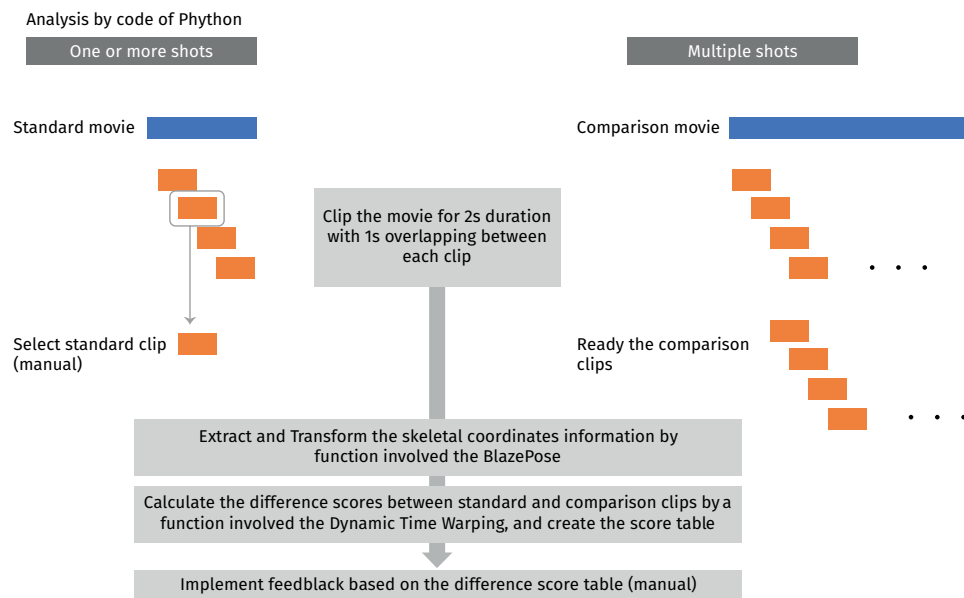


Figure 1. Overview of AI-based analysis.

These results were summarized in a score table that was sorted by the lowest total score and contained the scores of each body part. The score table is automatically output, and the results are interpreted by users.

The developed code can be demonstrated here (<https://drive.google.com/drive/folders/11UG48uyxXfjIUTE6v5YGk9eZ109WRPdU?usp=sharing>).

Evaluation

To achieve this goal, we conducted two evaluations. The first was to evaluate whether similar phase clips (i.e., from toss-up to immediately after the impact) were in the upper part of the score table to clarify whether the AI-based analysis extracted the overlapping phase of the standard clip from the comparison clips. To conduct the evaluation, the following conditions for service videos from the two study participants were gathered: 1st and 2nd services for five shots on the deuce and advantage sides, respectively. The collected videos were used to conduct an AI-based analysis of comparisons within the same condition, between different conditions, and between different players; 12 conditions were conducted. The accuracy (%) was calculated by referring to previous studies (Cai et al., 2020; O Conaire et al., 2010). Notably, the top 12 clips within the same condition and top 15 clips between different conditions and players from the score table were considered for the calculation. Specifically, the accuracy was calculated by dividing the number of correct detections (i.e., overlapping the phase) by the total number of compared files. The top clips were considered because clipped comparison movies were assumed to contain at least 12 or 15 overlapping phase clips with the standard clip. The 2 s standard clip mostly contained the entire phase of service whilst the comparison movies contained

four shots in the case of the same condition, and five shots in the case of different conditions and players. Therefore, although the number of clips for a single shot is dependent on the timing of clipping, a single shot can be clipped for three clips with 1 s overlap. Accordingly, the number of targeting clips was calculated by multiplying three movies by four or five shots. In addition, Spearman correlation coefficients (ρ) between correct detection and difference scores were calculated to understand these relationships.

The second objective was to evaluate the correspondence between manual and AI-based analyses for the detection of different movements in each body part. The target clips for the evaluation were set as standard clips, and one comparison clip showed the lowest total score in the first evaluation under each condition. When the clip did not have an overlapping phase between clips, the clip with the second-lowest total score was used. Manual evaluation was conducted by one of the authors who is a qualified Japan Sports Association Instructor of Tennis. The evaluator observed and compared the clips from the perspective of different movements and described applicable body parts that had different movements from the standard clip. As the left shoulder was set as the origin, this part was excluded from the evaluation. The evaluation was conducted under concealed conditions based on the results of the AI-based analysis. After completion of the manual evaluation, body parts with any description were compared with the scores and ranks of the AI-based analysis.

The evaluation of shot movement was conducted using the open-source movement analysis software Kinovia (<https://www.kinovea.org/>) and its functions, such as two playback screens, slow motion, and rewinding. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp. was used for data analysis. The level of statistical significance was set at $P < 0.05$.

RESULTS

Table 1 shows the accuracy of extracting the overlapping phase of the standard clip from the comparison clips. The duration of the target videos ranged from 34 to 45 s; thus, 34 to 45 clips were created. The average accuracy when comparing within the same condition was 79.2 % for both deuce and advantage sides. The average accuracy when comparing between different conditions were as follow: 73.3 % in case of side comparison, 70.0 % in case of the first and second service comparisons in both deuce and advantage sides. Among these, the accuracy in case of the side comparison for Player 2 was the lowest (46.7 %), whilst that between different players was 80.0 and 40.0 % for the deuce and advantage sides, respectively.

Table 2 shows the correlation between the correct detection and difference scores. The total and difference scores for each body part mostly showed a negative correlation with correct detection, which indicates that clips with lower difference scores are more likely to overlap. For the overall correlations, all difference scores showed a statistically significant correlation with correct detections. Moreover, side comparison for Player 2, which showed low accuracy of 46.7 %, had statistically positive correlation in the nose ($\rho = 0.35$), left elbow ($\rho = 0.48$), and left wrist ($\rho = 0.40$). For the different players' comparison in the advantage side (accuracy: 40.0 %), some body parts showed statistically significant negative correlations

(left elbow: $\rho = -0.36$ and left wrist: $\rho = -0.35$) while five body parts showed positive correlations.

Table 3 shows a comparison of the results between the manual and AI-based analyses for comparison within the same conditions. For the deuce side of Player 2, the manually evaluated body parts that showed different movements corresponded to the top three different parts in the AI-based analysis. However, for the deuce side for Player 1 and the advantage side for Player 2, manually evaluating different movements of the body parts had the lowest difference scores in the AI-based analysis (considered to be similar movements). For the advantage side of Player 1, there were no confirmed body parts that had different movements in the manual evaluation, whereas the left elbow showed the highest difference score.

Table 4 shows a comparison of the results of the manual and AI-based analyses for different conditions. One of the manually evaluated body parts that exhibited different movements corresponded to the top three different parts in the AI-based analysis under all conditions.

Table 5 shows a comparison of the results of the manual and AI-based analyses for different players. On the source side, two of the manually evaluated body parts that showed different movements corresponded to the top two or three parts in the AI-based analysis. For the advantage side, manually evaluated different movements of body parts were the top four difference scores in the AI-based analysis.

Table 1.
Accuracy for extracting overlapped phase of the standard clip from the comparison clips.

Condition		Player 1		Player 2		Total	
Standard	Comparison	Number of correct detections	Accuracy (%)	Number of correct detections	Accuracy (%)	Number of correct detections	Accuracy (%)
Comparison within same condition							
1st service, deuce side	-	11	91.7	8	66.7	19	79.2
1st service, advantage side	-	11	91.7	8	66.7	19	79.2
Comparison within different conditions							
1st service, deuce side	1st service, advantage side	15	100.0	7	46.7	22	73.3
1st service, deuce side	2nd service, deuce side	12	80.0	9	60.0	21	70.0
1st service, advantage side	2nd service, advantage side	10	66.7	11	73.3	21	70.0
Comparison within different players							
1st service, deuce side	-	-	-	-	-	12	80.0
1st service, advantage side	-	-	-	-	-	6	40.0

The top 12 or 15 similar comparison clips were targeted for each condition.
Accuracy (%) = number of correct detections / total number of compared files.

Hips, knees and ankles

Condition		Player	Difference score														
			Total		Right hip		Left hip		Right knee		Left knee		Right ankle		Left ankle		
Standard	Comparison		ρ	P-value	ρ	P-value	ρ	P-value	ρ	P-value	ρ	P-value	ρ	P-value	ρ	P-value	
Comparison within same condition																	
1st service, deuce side	-	1	-0,42	0,01	-0,43	0,01	-0,28	0,09	-0,49	0,00	-0,18	0,28	-0,45	0,01	-0,19	0,26	
		2	-0,21	0,17	-0,07	0,65	0,00	1,00	-0,49	0,00	-0,44	0,00	-0,39	0,01	-0,40	0,01	
1st service, advantage side	-	1	-0,54	0,00	-0,16	0,37	-0,25	0,15	-0,34	0,05	-0,29	0,10	-0,34	0,05	-0,37	0,03	
		2	-0,01	0,94	-0,06	0,72	0,04	0,79	0,06	0,69	0,12	0,45	0,14	0,37	0,25	0,11	
Comparison between different conditions																	
1st service, deuce side	1st service, advantage side	1	-0,59	0,00	-0,52	0,00	-0,43	0,01	-0,46	0,01	-0,46	0,01	-0,45	0,01	-0,24	0,17	
		2	0,10	0,53	-0,10	0,52	-0,05	0,72	-0,20	0,20	-0,22	0,14	-0,17	0,26	-0,28	0,06	
1st service, deuce side	2nd service, deuce side	1	-0,40	0,02	-0,45	0,01	-0,34	0,05	-0,45	0,01	-0,14	0,44	-0,32	0,06	-0,07	0,68	
		2	-0,10	0,51	0,15	0,34	0,24	0,13	-0,19	0,22	-0,05	0,78	-0,20	0,20	-0,06	0,70	
1st service, advantage side	2nd service, advantage side	1	-0,23	0,17	-0,02	0,93	-0,08	0,64	-0,10	0,57	-0,26	0,13	-0,01	0,98	-0,08	0,64	
		2	-0,08	0,59	-0,09	0,56	-0,05	0,76	-0,09	0,55	-0,17	0,27	-0,10	0,53	-0,24	0,12	
Comparison between different players																	
1st service, deuce side	-	1	-0,27	0,07	0,00	0,97	-0,24	0,10	-0,19	0,22	-0,28	0,06	-0,08	0,60	-0,15	0,31	
1st service, advantage side	-	2	-0,12	0,45	0,08	0,58	0,15	0,32	0,03	0,86	-0,03	0,86	-0,16	0,30	-0,21	0,17	
Overall			-0,20	0,00	-0,12	0,01	-0,09	0,05	-0,20	0,00	-0,18	0,00	-0,17	0,00	-0,15	0,00	

Table 3.
Comparison of the results between manual and AI-based analysis for the comparison within the same condition.

Items	Body parts														Note
	Nose	Right shoulder	Left shoulder	Right elbow	Left elbow	Right wrist	Left wrist	Right hip	Left hip	Right knee	Left knee	Right ankle	Left ankle		
1st service, deuce side, Player 1															
Manual analysis			Reference								Deeply bent when toss-up				
AI-based analysis	Difference score	13,17	14,08	13,24	12,79	13,09	12,4	13,21	12,16	12,28	11,1	12,07	11,41		
	Rank of difference	4	1	2	6	5	7	3	9	8	12	10	11		
1st service, deuce side, Player 2															
Manual analysis			Reference						Down at the impact (whole body tilted to the left)						
AI-based analysis	Difference score	14,26	13,14	13,89	14,22	13,96	14,68	14,8	14,54	14,06	13,71	13,76	13,58		
	Rank of difference	4	12	8	5	7	2	1	3	6	10	9	11		
1st service, advantage side, Player 1															
Manual analysis			Reference												Limited overlapped phase (only for toss-up), no different parts observed manually
AI-based analysis	Difference score	14,89	14,04	13,74	15,16	13,67	14,88	13,87	13,61	14,14	14,13	14,91	15,05		
	Rank of difference	4	8	10	1	11	5	9	12	6	7	3	2		
1st service, advantage side, Player 2															
Manual analysis			Reference	Located slightly on the outside after the impact (the side is open)											
AI-based analysis	Difference score	12,75	14,07	12,72	12,82	12,85	12,91	13,05	13,51	12,87	13,02	13,04	13,41		
	Rank of difference	11	1	12	10	9	7	4	2	8	6	5	3		

Table 4.
Comparison of the results between manual and AI-based analysis for the comparison between different conditions.

Nose, shoulders, elbows and wrists

Items	Body parts							Note
	Nose	Right shoulder	Left shoulder	Right elbow	Left elbow	Right wrist	Left wrist	
1st service, deuce side - advantage side, Player 1								
Manual analysis		Closer to parallel to the net when the toss-up (also the direction of whole body)	Reference					
AI-based analysis	Difference score	14	14,49		13,32	14,12	13,39	14,04
	Rank of difference	4	1		11	2	10	3
1st service, deuce side - advantage side, Player 2								
Manual analysis			Reference			Large follow-through on landing after the impact		Limited overlapped phase (only for follow-through)
AI-based analysis	Difference score	15,18	15,68		15,82	14,95	15,27	14,96
	Rank of difference	4	2		1	6	3	5
1st - 2nd service, deuce side, Player 1								
Manual analysis		More perpendicular to the ground just before the impact (more shoulder abduction)	Reference	Swing more to the upper right immediately after the impact				
AI-based analysis	Difference score	13,72	12,82		13,69	13,52	13,59	12,88
	Rank of difference	2	10		3	6	4	8
1st - 2nd service, deuce side, Player 2								
Manual analysis			Reference				Large swing-up on landing after the impact	
AI-based analysis	Difference score	13,33	13,48		15,11	14,09	15,21	14,29
	Rank of difference	12	11		2	5	1	3

Nose, shoulders, elbows and wrists (Continued)

1st - 2nd service, advantage side, Player 1								
Manual analysis		Almost parallel to the net when toss-up (and overall body orientation as well)			Reference	Bended on landing after the impact		
AI-based analysis	Difference score	13,31	12,76		13,48	13,79	13,42	14
	Rank of difference	8	12		4	2	5	1
1st - 2nd service, advantage side, Player 2								
Manual analysis		Reference						
AI-based analysis	Difference score	12,48	12,5		12,21	12,55	12,74	12,72
	Rank of difference	11	10		12	9	6	7

Hips, knees and ankles

Items	Body parts						Note
	Right hip	Left hip	Right knee	Left knee	Right ankle	Left ankle	
1st service, deuce side - advantage side, Player 1							
Manual analysis							
AI-based analysis	Difference score	13,41	13,44	13,63	13,09	13,97	13,64
	Rank of difference	9	8	7	12	5	6
1st service, deuce side - advantage side, Player 2							
Manual analysis		Rotated to the net side after the impact					Limited overlapped phase (only for follow-through)
AI-based analysis	Difference score	14,11	13,55	13,48	13,39	13,58	13,84
	Rank of difference	7	10	11	12	9	8
1st - 2nd service, deuce side, Player 1							
Manual analysis		Elevated higher position on landing after the impact					
AI-based analysis	Difference score	13,94	13,58	12,87	12,62	12,98	12,29
	Rank of difference	1	5	9	11	7	12
1st - 2nd service, deuce side, Player 2							
Manual analysis		The pelvis rotates to the net side at an earlier time just before the impact			The pelvis is abducted and positioned more outward at the impact		
AI-based analysis	Difference score	14,04	13,76	14,15	13,71	14,05	13,97
	Rank of difference	7	9	4	10	6	8

Hips, knees and ankles (Continued)

1st - 2nd service, advantage side, Player 1							
Manual analysis		Slow pelvic rotation to the net side from just before the impact to its end					
AI-based analysis	Difference score	13,38	13,25	13,22	13,4	13,3	13,56
	Rank of difference	7	10	11	6	9	3
1st - 2nd service, advantage side, Player 2							
Manual analysis		Slow pelvic rotation to the net side from just before the impact to its end			The pelvis is abducted and positioned more outward at the impact		
AI-based analysis	Difference score	12,77	12,58	13,43	13,87	13,88	14,07
	Rank of difference	5	8	4	3	2	1

Table 5. Comparison of the results between manual and AI-based analysis for the comparison between different players

Items		Body parts												Note
		Nose	Right shoulder	Left shoulder	Right elbow	Left elbow	Right wrist	Left wrist	Right hip	Left hip	Right knee	Left knee	Right ankle	
1st service, deuce side, Player 1-2														
Manual analysis			Reference		Not swung up on landing after the impact (shoulder not abducted)		More perpendicular to the ground when loss-up (more shoulder abduction)		The pelvis rotates to the net side early just before the impact				The pelvis is abducted and positioned more outward at the impact	
AI-based analysis	Difference score	13.87	14.78		14.39	14.3	14.48	14.51	14.72	13.99	13.18	12.84	13.41	12.99
	Rank of difference	8	1		5	6	4	3	2	7	10	12	9	11
1st service, advantage side, Player 1-2														
Manual analysis		Looking up when loss-up (neck is extended)	Reference											Limited overlapped phase (only for loss-up)
AI-based analysis	Difference score	15.1	14.13		14.61	13.26	14.03	13.4	15.2	15.48	15.45	14.68	13.8	13.75
	Rank of difference	4	7		6	12	8	11	3	1	2	5	9	10

DISCUSSION

This study developed an AI-based performance analysis for tennis coaching and investigated its accuracy in detecting similarities and differences within the same shot movement. As a result, a certain accuracy ($\geq 70\%$) was confirmed for detecting overlapping phases between clips. Moreover, the manually evaluated body parts that showed different movements corresponded favorably to the results of the AI-based analysis. Based on these results, the developed analysis can play a supportive role in finding observation points in tennis coaching.

Previous studies (Cai et al., 2020; Ó Conaire et al., 2010; Shah et al., 2007; Zhu et al., 2006) have mostly focused on shot classification (service, forehand, or backhand stroke). This study was conducted from an original perspective that attempted to extract similar phases. Results show that the accuracy was as high as 79.2 % when comparing within the same conditions, in the 70.0 - 73.3 % range when comparing between different conditions, and 80.0 % when comparing between different players in the deuce side. In a recent study (Cai et al., 2020), it was reported that a machine learning-based analysis was able to recognize 12 tennis actions with an accuracy of 62 %. Accordingly, most of the conditions in this study showed equivalent or higher accuracy than the previous study. The developed AI-based analysis is expected to provide effective feedback in coaching by automatically extracting overlapping phases with a certain accuracy.

However, low accuracy was confirmed under some conditions. Overall, accuracy was low for the conditions targeting Player 2. The lowest accuracy was observed in the side comparison for Player 2 (46.7 %). As the correlation with correct detection in the left elbow and wrist were mostly negative coefficients, except for the comparison within the same condition for Player 2, weighting these body parts for total difference scores would be effective in improving accuracy. Actually, when doubled the weight of difference scores in the left elbow and wrist for total score, the accuracy was 53.3%. The side comparison for Player 2 also showed low accuracy. It is possible that large differences in shot movements or positions between the sides affect the accuracy of extracting the overlapped phase. Adjusting or shortening the duration of clipping would be effective in improving accuracy. We attempted the solution for the side comparison for Player 2 by adjusting the clipping duration to 1 s with 0.5 s overlap. As the result, contrary to our expectations, the accuracy decreases to 6.6 %. Nevertheless, the adjustment of the clipping duration is also related to the phase length that the players and coaches want to focus on; thus, discretion of the user could be reflected. We assumed that the inclusion of extra movement after shots in the clips might have reduced accuracy, but this speculation was not applicable in this case. Another reason for the

low accuracy could be that Player 2 wore a similarly colored shirt, and the estimator of the AI-based analysis was not able to estimate the human pose by changing the side and recording angle. Further investigation is required to determine the conditions that lead to low accuracy in the analysis.

This study attempts to extract the differences within the same shot movement using AI-based analysis. A previous study performed a comparison within the same shot in tennis (Cai et al., 2020), however, it reported that there was considerable confusion regarding the accuracy of the comparison. This study attempted to extract information on the differences in the movements of each body part that might be required for coaching. As a result, manually evaluated body parts that showed different movements by a certified coach corresponded to the top three different parts in the AI-based analysis for 8 of the 12 conditions. Although manual interpretation by users, such as players and coaches, automatically provides information on which body parts show different movements, it would help in effective and accurate motion analysis. However, some conditions showed contradictory results between manual and AI-based analyses. In this regard, the comparison within the same condition on the deuce side for Player 1 and the advantage side for Player 2 had the highest difference score for the right shoulder in the AI-based analysis. This may be because the internal and external rotation of the shoulder during service is fast, and the AI-based analysis would be judged as significantly different because of the video recording setting. In any case, no significant difference was observed between the clips because the services were performed consecutively in the comparison under the same conditions. It is expected that AI-based analysis would be useful for comparison in conditions that would have large differences, such as between early and late stages in a match or before and after a specific practice. Practical investigation of the application is needed. If rallies are targeted in the future, guards should be installed to protect cameras from ball hits. In addition, different scores in some clips with limited overlapping phases might have affected the movement included only in either clip. This may be an issue in practical applications. The proposed AI-based analysis should be treated as a supplemental tool to help coaching because selecting the reference video and interpreting the differences in movements are required to be conducted manually by the players or coaches. Even if this AI-based analysis underlines the differences in movement, the coach's assistance is still necessary if the players themselves have difficulty interpreting these differences.

This study had several limitations. First, this study conducted video recordings under identical conditions (participants' wear, camera location, type and setting, weather, court color, background, etc.). Therefore, further investigation is required to determine whether

these conditions affect the analysis accuracy. Second, although variations in accuracy were observed in this study, this should be clarified by focusing on a variety of participants. Our aim was to compare services in various situations and investigate the perceptions of players and coaches to develop a useful AI-based analysis.

CONCLUSIONS

This study attempted to develop an AI-based analysis that plays a supportive role in tennis coaching, and investigated its accuracy-targeting services. Consequently, a certain accuracy in detecting similarities and differences between movements was confirmed. Although there were some issues that needed to be solved, this AI analysis could effectively extract similar or overlapping phases and suggest body parts that might have different movements.

DECLARATION OF CONFLICT OF INTEREST

Yusuke Satonaka, Ryosuke Wakamoto, and Michitaka Iida are employees of Information Services International-Dentsu, LTD, which supports digital transformation with solid technological and creative capabilities, and provided the programming code for the performance analysis in this study. To eliminate the possibility of bias, investigators were not involved in any data handling procedures.

FUNDING

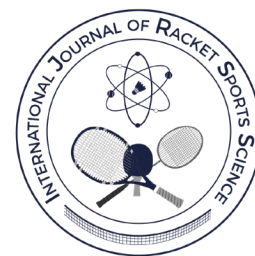
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Comparing smash performance and technique between elite male and female international badminton players

Comparación del rendimiento y la técnica del remate entre jugadores hombres y mujeres internacionales de élite de bádminton



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Abstract

Performance of the badminton smash plays a crucial role in success during competition. Differences in performance and technique between genders is of interest to players/coaches with respect to appropriate training intensity and understanding performance expectations during competition. Three-dimensional position data were collected for 26 male and 26 female elite international badminton players (world ranking: male = 59 ± 36 , female = 54 ± 24) performing the smash. Male players compared to female players performed smashes with greater shuttlecock speed (98.7 vs 78.5 m·s⁻¹; $p < 0.001$), racket head speed (63.3 vs. 51.0 ; $p < 0.001$), and shuttlecock angle below the horizontal (13.3° vs. 7.3° ; $p < 0.001$) with the latter likely due to higher contact heights (2.90 vs 2.46 m; $p < 0.001$) and jump heights (53.6 vs 14.5 cm; $p < 0.001$). Female players typically used a 'kick-through' rather than a 'two-footed jump' movement. The majority of differences in technique, assessed via statistical parametric mapping, occurred during the backswing phase, where male players adopted a more flexed, less laterally flexed (to non-racket-arm side) and counter-rotated trunk positions. Male players held their racket arm further back during the backswing (negative shoulder plane of elevation angle), and the elbow joint was held in a more extended position at the start of the backswing and in a more flexed position just prior to contact. No differences were found at the wrist joint. This study provides normative performance and technique data for elite male and female international players, highlighting current differences between genders which may inform training and competition preparation.

Keywords: racket, overhead, gender, kinematic.

Resumen

El rendimiento en el remate de bádminton desempeña un papel crucial en el éxito durante la competencia. Las diferencias en el rendimiento y la técnica entre sexos son de interés para los jugadores y los entrenadores con respecto a la intensidad de entrenamiento adecuada y a la comprensión de las expectativas de rendimiento durante la competencia. Se recogieron datos de la posición tridimensional de 26 jugadores y 26 jugadoras internacionales de élite de bádminton (clasificación mundial: hombres = 59 ± 36 , mujeres = 54 ± 24) al realizar el remate. Los hombres realizaron los remates con mayor velocidad del volante ($98,7$ vs $78,5$ m·s⁻¹; $p < 0,001$), mayor velocidad de la cabeza de la raqueta ($63,3$ vs $51,0$; $p < 0,001$) y mayor ángulo del volante por debajo de la horizontal ($13,3^\circ$ vs $7,3^\circ$; $p < 0,001$), este último probablemente debido a una mayor altura de contacto ($2,90$ vs $2,46$ m; $p < 0,001$) y de salto ($53,6$ vs $14,5$ cm; $p < 0,001$). Las mujeres solían saltar haciendo un movimiento de tijera en lugar de un movimiento con los dos pies. La mayoría de las diferencias en la técnica, evaluadas a través del mapeo paramétrico estadístico, se dieron durante la fase de backswing, en la que los hombres adoptaron una posición del tronco más flexionada,

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menos flexionada lateralmente (hacia el lado contrario al brazo de la raqueta) y contrarrotada. Los hombres mantuvieron el brazo de la raqueta más atrás durante el backswing (plano negativo del hombro del ángulo de elevación), y la articulación del codo se mantuvo en una posición más extendida al inicio del backswing y en una posición más flexionada justo antes del contacto. No se encontraron diferencias en la articulación de la muñeca. Este estudio proporciona datos normativos sobre el rendimiento y la técnica de jugadores hombres y mujeres internacionales de élite, y destaca las diferencias actuales entre los sexos que pueden servir de base para el entrenamiento y la preparación para la competencia.

Palabras clave: *raqueta, golpeo de mano alta, género, cinemática.*

INTRODUCTION

The badminton smash is a critical shot for successful performance and accounts for 54% of 'unconditional winner' and 'forced failure' shots in international competition (Tong & Hong, 2000), where successful performance is a function of both speed and direction (King et al., 2020). Of interest to researchers, biomechanists and coaches are the technique parameters that allow badminton players to perform faster smashes and/or more accurate smashes. The majority of research to date focused on biomechanics including elite players has focused exclusively on male badminton players (King et al., 2020; Ramasamy et al., 2021, Ramasamy et al., 2022), while very few have included female players (Ferreira et al., 2020).

Ferreira et al. (2020) studied 14 Polish national team players (seven male, seven female) focused primarily on upper extremity muscle strength and lower limb power, and their relationships with shuttlecock speed in the smash, both with and without a jump. Their analyses focused on performance outcomes, namely, the height of contact and shuttlecock speed. As expected on all upper extremity strength and lower limb power tests, males outperformed female players. Similarly, on all performance outcomes, the male players significantly (*large*: $\eta^2 = 0.853$) outperformed female players, on average producing shuttlecock speeds $15.7 \text{ m}\cdot\text{s}^{-1}$ and $14.4 \text{ m}\cdot\text{s}^{-1}$ faster during jump and no jump conditions, respectively, as well as contact points 44 cm higher when performing a jump smash (*large*: $\eta^2 = 0.780$). One limitation of comparing performance by post-impact speed in object-striking sports, such as badminton, is the effect of the impact mechanics where a poor impact results in a loss of performance despite a potentially large (but poorly timed) input from the athlete (McErlain-Naylor et al., 2020). Racket head speed could be considered a more appropriate measure of performance potential.

During the tennis serve, adolescent male players achieved greater maximum shoulder external rotation and front hip vertical velocity for both flat and kick serves (Connelly et al., 2019), however for Olympic-level players the only difference found was that male

players produced greater maximal shoulder internal rotation angular velocities than females ($2420 \text{ vs. } 1370^\circ\cdot\text{s}^{-1}$), achieving serve velocities approximately 22% faster (Fleisig et al., 2003). Therefore, with few significant differences in serve kinematics between male and female tennis players there would be no reason to coach different mechanics to males and females (Fleisig et al., 2003). Similar research within baseball pitching found that male players achieve greater upper torso/pelvis separation at stride foot contact and maximum elbow extension angular velocity during the arm acceleration phase, ultimately achieving ball velocities approximately 35% faster (Chu et al., 2009).

Previous research into kinematic differences during the golf swing between male and female golfers centred around pelvis and thorax rotations (Egret et al., 2006; Horan et al., 2010, 2011; Zheng et al., 2008). Interestingly these differences do not pertain to pelvis-thorax separation (Horan et al., 2010), which was correlated with greater shuttlecock speed in male badminton players (King et al., 2020). In cricket power hitting, McErlain-Naylor et al. (2021) found that male batters produced greater maximum bat speeds, ball launch speeds, and ball carry distances than similarly skilled female batters, and after controlling for the body mass and height, found that the male batters had greater pelvis-thorax separation in the transverse plane at the initiation of the downswing (similar to the start of the forward swing in the badminton smash), and extended their lead elbows more during the downswing.

From a dynamical systems theory perspective, the interaction of organismic, environmental, and task constraints determine individual movement patterns (Kelso, 1995; Newell, 1996). Any differences in performance and movement patterns between male and female badminton players may be due to differences in the above constraints which exist in all cases or on average (McErlain-Naylor et al., 2021). These constraints include anthropometry (Stuelcken et al., 2007), force-velocity relationships (Torrejón et al., 2019), and racket inertial properties (Creveaux et al., 2013). The aim of the present study was to identify the differences in performance and technique of the badminton smash between elite male and

female badminton players only, without suggesting casual factors i.e., controlling for height and mass (McErlain-Naylor et al., 2021). It was hypothesised that male players would produce greater shuttlecock speeds, racket head speeds, and steeper trajectories. Additionally, it was hypothesised that male players would achieve a greater jump height and greater x-factor (pelvis-thorax separation).

MATERIAL AND METHODS

Participants

26 males (age 25.5 ± 4.6 years; height 1.82 ± 0.06 m; mass 75.9 ± 4.0 kg) and 26 females (age 23.0 ± 2.7 years; height 1.71 ± 0.07 m; mass 63.6 ± 8.9 kg) participated in this study. Participants were all international level competing at the BWF World Championships and/or Yonex All England Championships and/or members of the England/Great Britain national squad. The dataset included a mixture of singles and doubles players, where the average world ranking was 59 ± 36 and 54 ± 24 for male and female players, respectively (based on their highest ranking in all disciplines at the time of testing). All participants were free from any injuries that may affect their performance and participation in the study. Testing procedures were explained to participants in accordance with Loughborough University ethical guidelines, and subsequently, informed consent was obtained.

Data collection

All testing was conducted on a badminton (practice) court at two international events and a national training centre. These were the BWF World Championships, Glasgow, UK; Yonex All England Badminton Championships, Birmingham, UK; and National Badminton Centre, Badminton England.

Markers were attached to bony landmarks, racket, and shuttlecock consistent with King et al. (2020). Three-dimensional kinematic data were collected using a Vicon Motion Analysis System (OMG Plc, Oxford UK) operating at 400 Hz. All participants completed a self-selected warm-up and were given multiple trials to become familiar with the delivery of the incoming shuttlecock. Two methods of delivery were used: a racket-feed from an ex-international badminton player and a shuttlecock launcher (BKL, Badenko, France) launching every three seconds, both deemed representative of a lift stroke in competitive play by an international player. Given the high standard of the participants, the multiple methods used to deliver the shuttlecock was assumed not to affect subsequent performance. Participants were instructed to smash as fast as possible using their normal technique, completing approximately 25 trials (five sets of five), with variation due to loss of markers.

Data analysis

Racket and shuttlecock marker data for all trials were labelled within Vicon Nexus software (OMG Plc, Oxford, UK). The curve-fitting methodology of McErlain-Naylor et al. (2020) adapted from cricket (Peplow et al., 2014) was used to calculate racket and shuttlecock kinematic variables (maximum shuttlecock speed, racket head speed at contact, height at contact, shuttlecock angle at start of flight), where a precise time of impact was calculated for a more accurate determination of these variables. Note that the contact period was amended from 1 to 1.4 ms, in accordance with Towler et al. (2023). The best trial (i.e., greatest post-impact shuttlecock speed) was identified and used for further investigation.

Whole-body marker data for the best trial per participant were labelled within Vicon Nexus. To avoid problems with filtering through the racket-shuttlecock impact, the 'linear extrapolation' method was utilised by extrapolating pre-impact data through impact (Knudson & Bahamonde, 2001). Marker trajectories were then filtered using a recursive two-way Butterworth low-pass filter with a cut-off frequency of 30 Hz determined by residual analysis (Winter, 2009). Technique variables (joint angles) were calculated using Cardan/Euler sequences recommended for each joint (Wu et al., 2005, Smith et al., 2015; Table 1), where the x, y and z axes were unit vectors representing the mediolateral, anterior-posterior and longitudinal axes, respectively (Worthington et al., 2013). Left-handed players' global position data in the x-axis was multiplied by -1, such that they could be considered right-handed. An offset was applied to the wrist flexion angles based on the placement of the hand marker which protruded from the back of the hand.

Table 1.
Euler/Cardan sequences used to calculate joint angles

joint	sequence	rotations
shoulder	z-y-z ¹	plane of elevation, elevation, internal rotation
elbow	x-y-z ¹	flexion, abduction, pronation (proximal)
wrist	x-y-z ¹	flexion, ulnar deviation, pronation (distal)
trunk	y-x-z ²	lateral flexion, flexion, axial rotation (x-factor)

Recommendation by: ¹ Wu et al. (2005), ² Smith et al. (2015).

All joint angle data were normalised to represent the swing phase, the start of the swing was calculated as the frame in which the racket head centre speed exceeded $5 \text{ m}\cdot\text{s}^{-1}$ from which it did not decrease until impact, to exclude any random movement of the racket prior to the swing commencing. The end of the swing phase was defined as the last frame before impact, calculated using the curve-fitting

methodology. The swing duration was also selected as a performance variable.

Whole body centre of mass was calculated using individual segment inertial values (Yeadon, 1990), where the body was modelled as 14 segments. Jump height was then calculated as the vertical distance between the maximum centre of mass height and the centre of mass height during a static standing trial. Height of contact was calculated as the vertical position of the shuttlecock at the last frame prior to impact.

Statistical analysis

All statistical analyses were performed in SPSS v.28.0. (IBM Corp., Armonk, NY, USA). Data were presented as mean ± standard deviation. Independent samples t-tests (t) were used to compare performance variables between genders, unless data were not normal, assessed by the Shapiro-Wilk test, in which case the Mann-Whitney U statistic (U) was used. A statistically significant threshold of $p < 0.05$ was used. Effect sizes were calculated using Cohen’s *d* and interpreted as: *trivial* < 0.2; $0.2 \leq$ *small* < 0.6; $0.6 \leq$ *moderate* < 1.2; $1.2 \leq$ *large* < 2.0; *very large* ≥ 2.0 (Hopkins et al., 2009). For Mann-Whitney U test, the effect size was calculated as $r = \frac{|z|}{\sqrt{n}}$, and interpreted as: *trivial* < 0.1; $0.1 \leq$ *small* < 0.3; $0.3 \leq$ *moderate* < 0.5; $0.5 \leq$ *large* < 0.7; *very large* ≥ 0.7 (Cohen, 1988; Hopkins et al., 2009).

SPM two-tailed independent sample t-tests ($p < 0.05$) were used to compare the joint angle time series between males and females (Pataky, 2010). SPM analyses were implemented using the open-source spm1d code on Matlab (v.M0.1, www.spm1d.org (accessed on 10 June 2023)).

RESULTS

Performance variables

Males generated significantly greater shuttlecock speeds, $98.7 \pm 3.6 \text{ m}\cdot\text{s}^{-1}$ vs. $76.5 \pm 8.2 \text{ m}\cdot\text{s}^{-1}$ ($U = 0$; p

< 0.001; Table 2) and racket head speeds $63.3 \pm 2.9 \text{ m}\cdot\text{s}^{-1}$ vs. $51.0 \pm 4.7 \text{ m}\cdot\text{s}^{-1}$ ($U = 0$; $p < 0.001$). Note that a U statistic of 0 indicates that the ranks of all male values were higher than those of all the females. Male players also developed greater racket head speeds using shorter (duration) swings, on average 28 ms shorter ($183 \pm 15 \text{ ms}$ vs. $211 \pm 33 \text{ ms}$; $t_{(50)} = -3.98$; $p < 0.001$; Figure 1).

Males also generated significantly steeper smashes on average 6° further below the horizontal ($t_{(50)} = 9.04$; $p < 0.001$), presumably due to significantly higher contact heights, on average 0.44 m higher ($t_{(50)} = 11.39$; $p < 0.001$), as a result of greater jump heights, which were on average 39.1 cm higher ($U = 5$; $p < 0.001$).

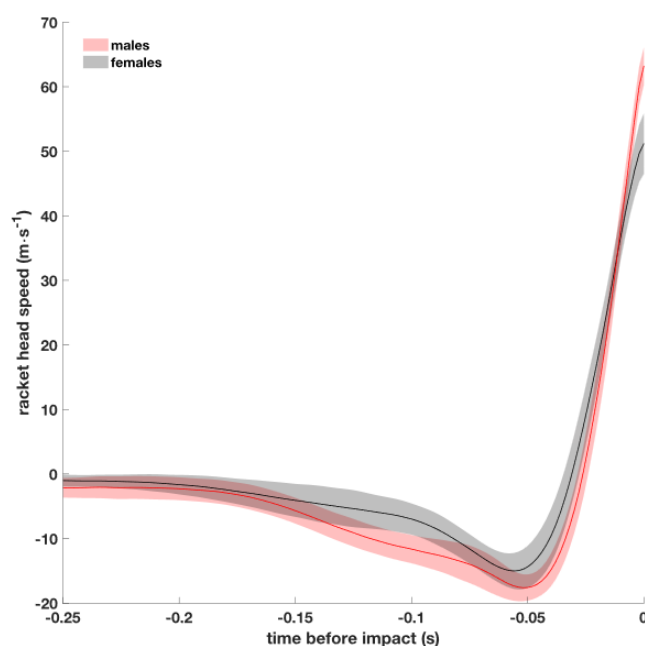


Figure 1. Differences in racket head speed development between males and females. Racket-shuttlecock contact occurs at $t = 0 \text{ s}$. Racket head speed is the velocity of the racket head centre velocity acting normal to the racket stringbed.

Table 2
Performance variable comparison between males and females

parameter	male	female	t [U]	d [r]	interpretation	p
shuttlecock speed ($\text{m}\cdot\text{s}^{-1}$)	98.7 ± 3.6	78.5 ± 8.2	[0.00]	[0.86]	very large	<0.001
racket head speed ($\text{m}\cdot\text{s}^{-1}$)	63.3 ± 2.9	51.0 ± 4.7	[0.00]	[0.86]	very large	<0.001
swing duration (ms)	183 ± 15	211 ± 33	-3.98	-1.11	moderate	<0.001
shuttlecock vertical angle ($^\circ$)	13.3 ± 2.2	7.3 ± 2.6	9.04	2.51	very large	<0.001
contact height (m)	2.90 ± 0.13	2.46 ± 0.15	11.39	3.16	very large	<0.001
jump height (cm)	53.6 ± 9.4	14.5 ± 11.0	[5.00]	[0.85]	very large	<0.001

t and d or U and r represent the statistics for an independent samples t-test or the Mann Whitney U test, respectively
tshuttle vertical angle refers to the angle below the horizontal

Technique variables

Male players had smaller trunk extension angles (more flexed) during 17-59% of the swing phase (Figure 1). Male players had smaller trunk lateral flexion angles (towards the left for a right-handed player) during 0-69% of the swing phase (Figure 2). Male players also adopted more counter-rotated (x-factor) positions during 0-73% of the swing phase and on average had marginally greater x-factor angles (Figure 3). Thus, male players used larger ranges of motions at the trunk, particularly x-factor, and lateral flexion, throughout the swing phase compared to females.

At the shoulder joint, the male players had a smaller plane of elevation angle between 0-56% of

the swing phase i.e., the racket arm was held back further (Figure 4). There was no difference in the elevation angle or internal rotation angle throughout the swing phase between genders (Figures 5 and 6).

At the elbow joint, the elbow extension angle had two regions of interest, firstly from 0-37%, where male players adopted more extended positions. Secondly, leading up to racket-shuttlecock contact (97-100% of the swing phase), male players adopted more flexed positions (Figure 7). Therefore, throughout the swing phase, male players used a smaller range of motion of elbow extension. At the wrist joint, there were no differences in wrist flexion and wrist ulnar/radial deviation angles throughout the entirety of the swing phase (Figures 8 and 9).

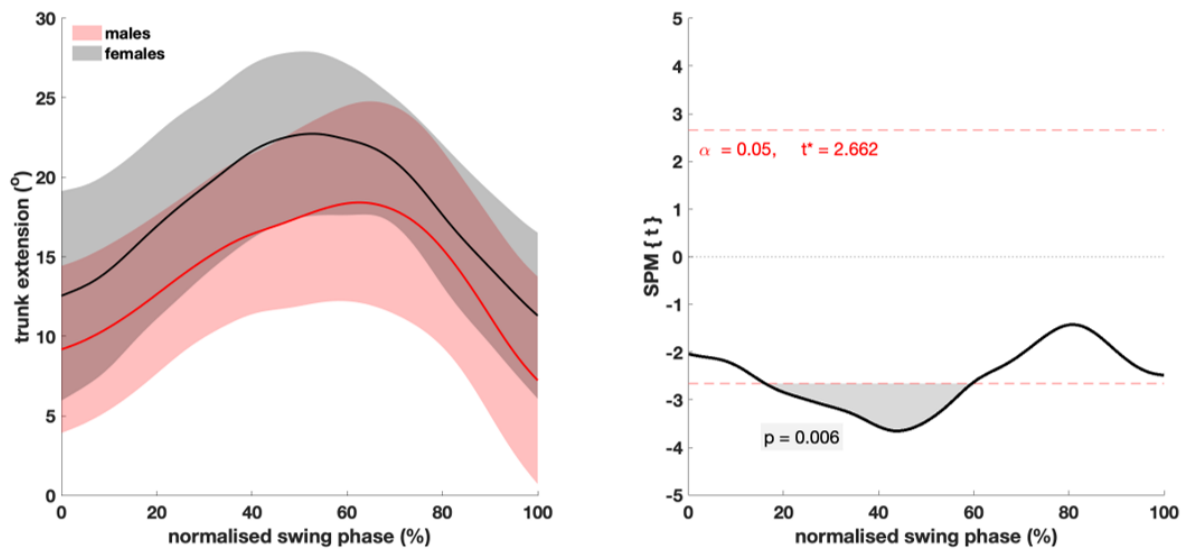


Figure 2. Trunk extension angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right)

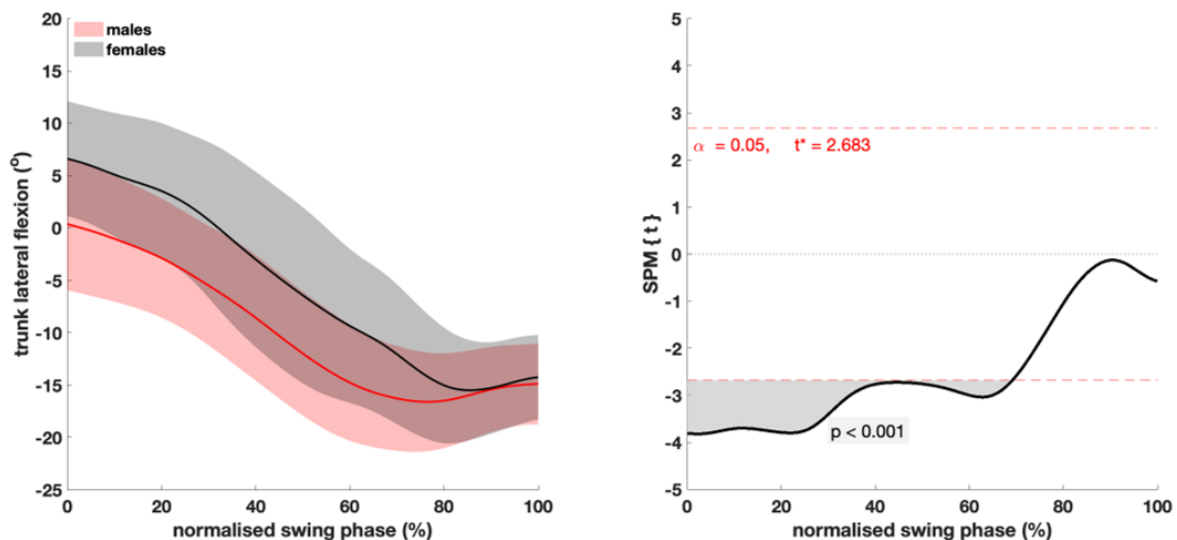


Figure 3. Trunk lateral flexion angles (towards the left for a right-handed player) during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

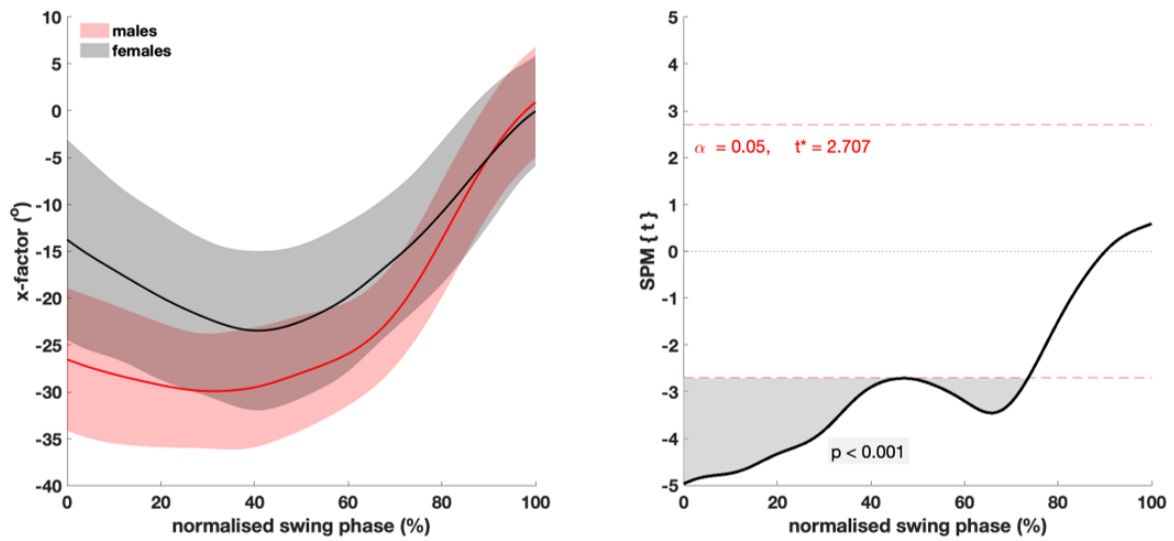


Figure 4. Trunk axial rotation (x-factor) angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

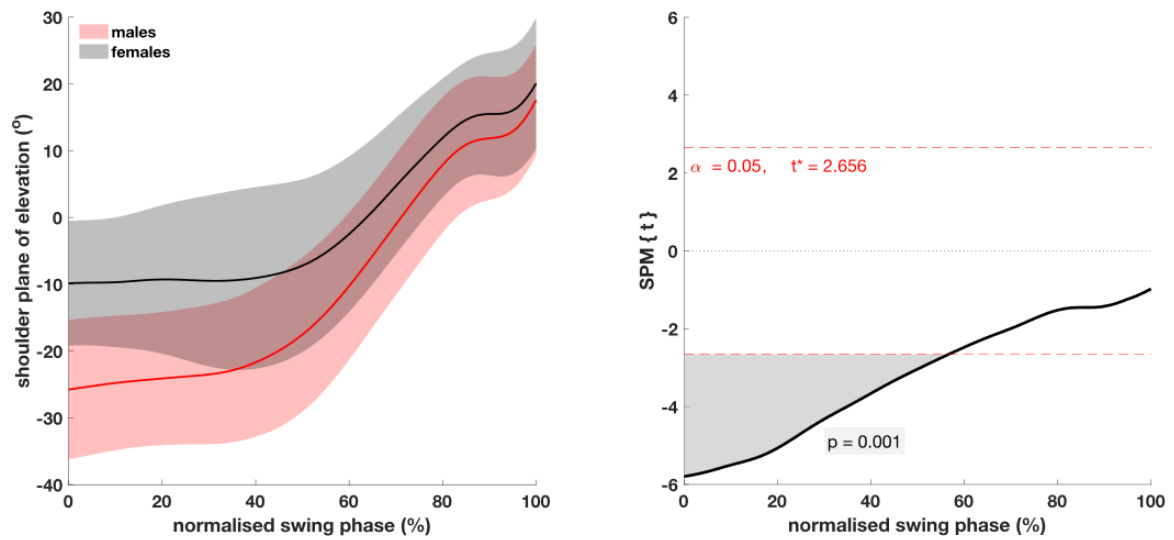


Figure 5. Shoulder plane of elevation angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

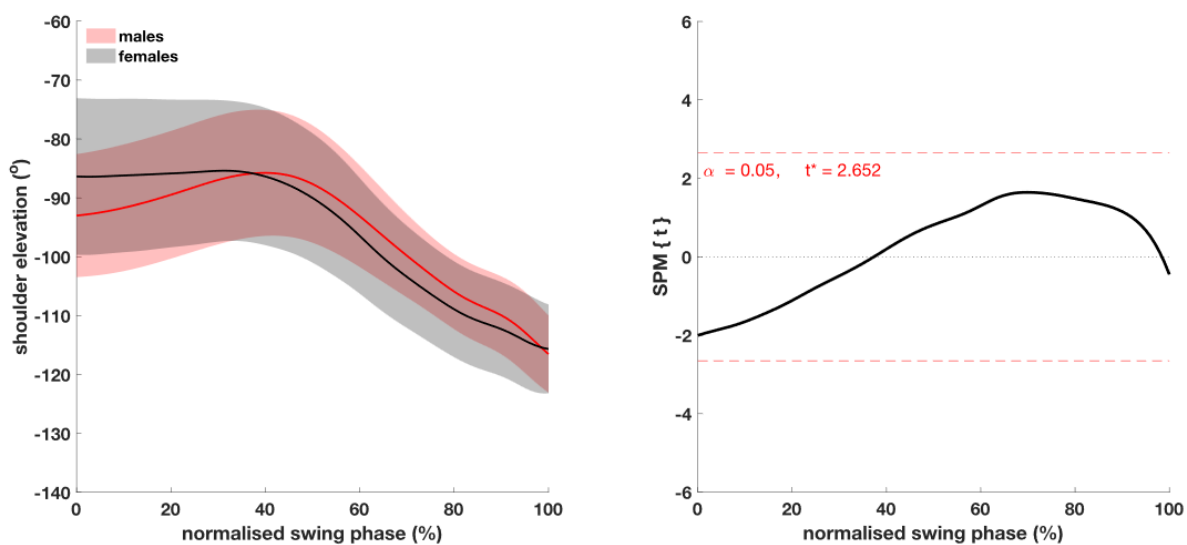


Figure 6. Shoulder elevation angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right)

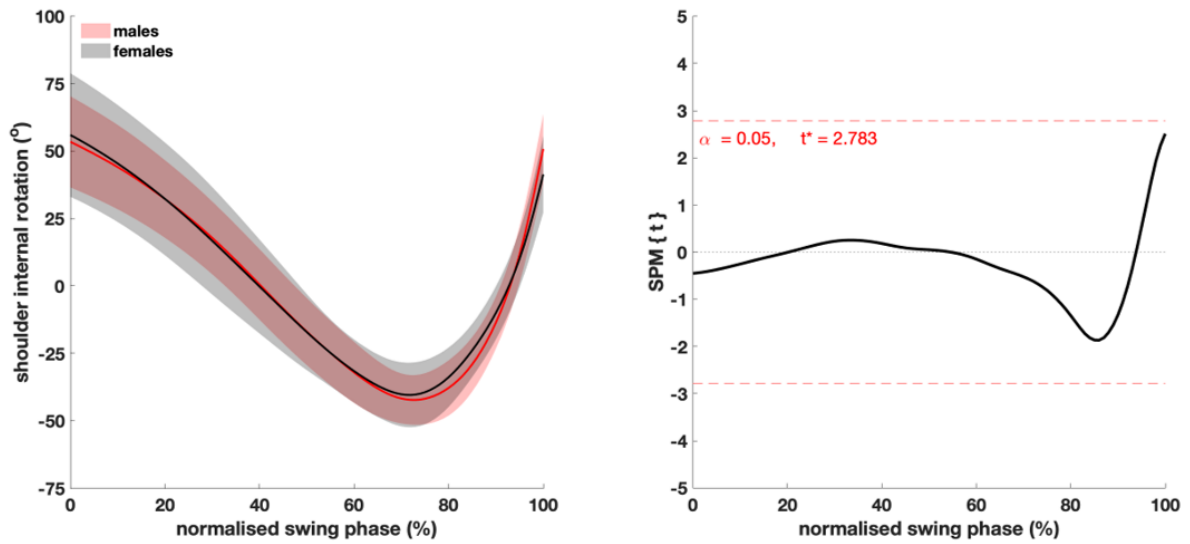


Figure 7. Shoulder internal rotation angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right)

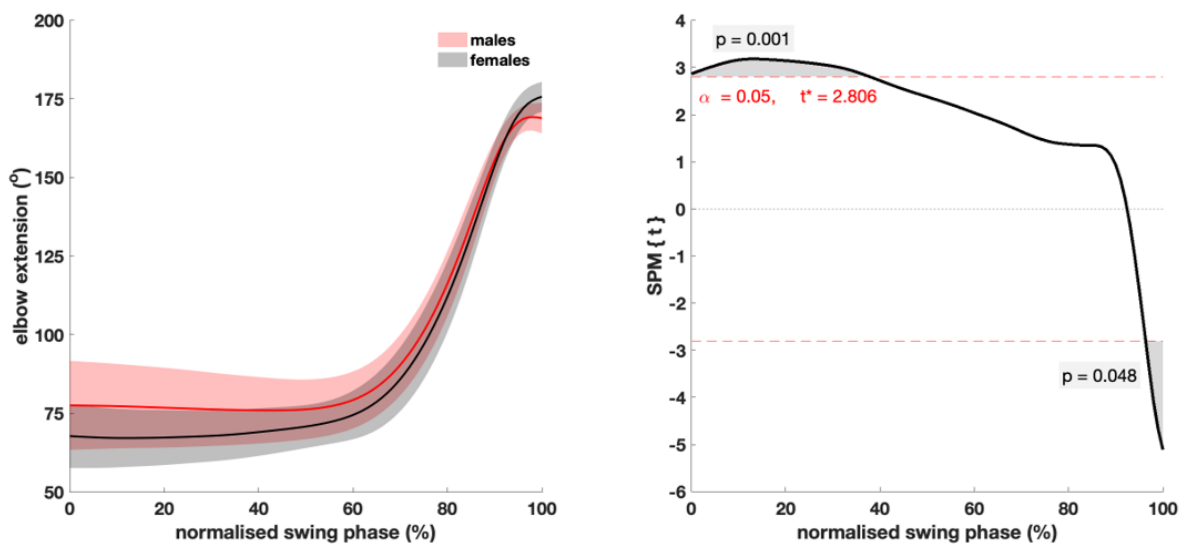


Figure 8. Elbow extension angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

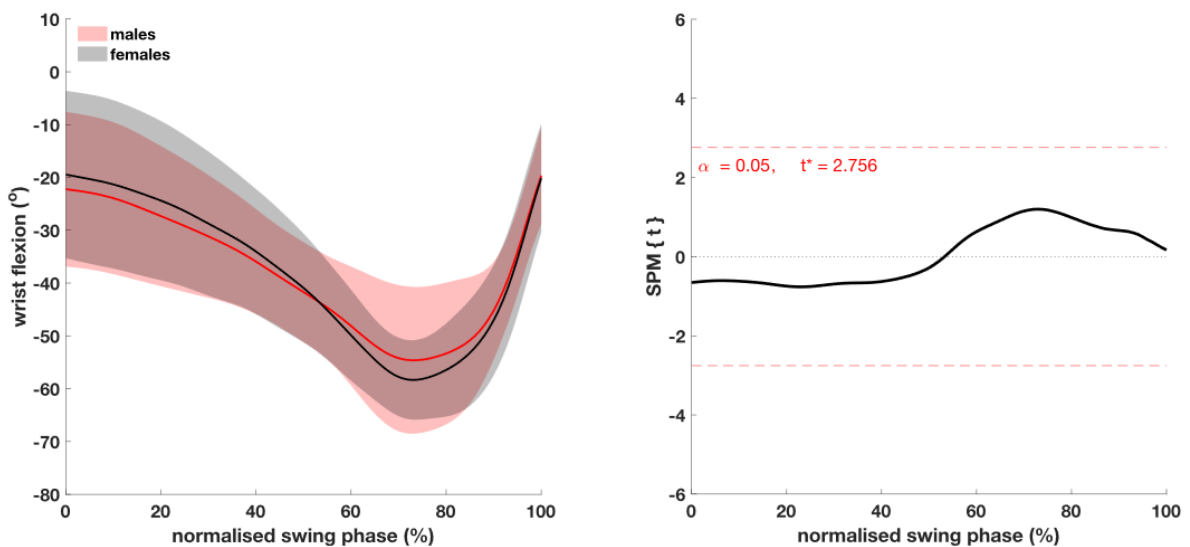


Figure 9. Wrist flexion angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

DISCUSSION

Males outperformed females for all performance variables. With respect to shuttlecock speed and racket head speed, males achieved $20.2 \text{ m}\cdot\text{s}^{-1}$ (25.7%) and $12.2 \text{ m}\cdot\text{s}^{-1}$ (23.9%) greater speeds than females. Similar performance differences have been observed in badminton (Ferreira et al., 2020) as well as other overhead sporting actions such as baseball pitching and the tennis serve (Chu et al., 2009; Fleisig et al., 2003). Differences were also evident relating to the shuttlecock trajectory (vertical angle) and the factors relating to the achievable vertical angle i.e., players that can achieve greater contact heights either through height or movement technique are able to achieve steeper vertical angles whilst still achieving a successful smash over the net. It is common in badminton for elite male players to perform a two-footed jump during their maximal smash technique, whereas female players tend to use a 'kick-through' movement which requires less elevation from the ground. Possible explanations for this difference include the physical capacity of males vs. females to perform the two-footed jump movement repeatedly through greater neuromuscular development and the ability to attenuate landing forces (Quatman et al., 2006). Secondly, as male players produce higher shuttlecock velocities, they use the smash more frequently to win points (Abian-Vicen et al., 2013).

By combining velocity, trajectory and contact point to describe a typical elite and female smash, it is possible to understand how the differences affect the difficulty for an opponent attempting to return the smash. Using the average speed and vertical angle, it was assumed that the male and female players made contact at the same location within the global transverse plane (xy), with only the z coordinate differing (males: 2.90 m, females: 2.46 m). The initial velocity was then modelled

as $98.7 \text{ m}\cdot\text{s}^{-1}$ acting 13.3° below the horizontal for males and $78.5 \text{ m}\cdot\text{s}^{-1}$ acting 7.3° below the horizontal for females, based on the average performances from each cohort, with both having zero velocity in the mediolateral direction (Figures 10 and 11).

The model showed that theoretically from contact to landing the male smash took 0.41 s to land, whilst the female smash required 0.61 s (+49%). The total flight time is of course linked to the trajectory, and the female smash landed 0.87 m further into court. For the female smash to reach the same anterior-posterior position on the court as the male smash at landing an additional 0.08 s (+20%) was required. For an opponent this means they have the option to either position themselves closer to the net to return the smash from a female, potentially allowing greater chances to play a counter-defensive stroke, or to remain in a similar position and give themselves more time to play an effective defensive stroke. Additionally, the contact point when returning the female smash would be higher, which would again give more options to the opponent for playing a more successful return.

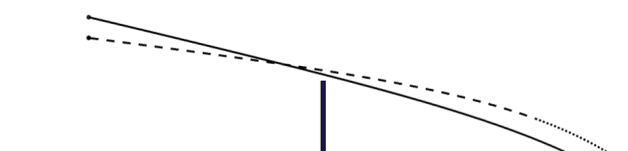


Figure 11. The solid lines represent $t = 0-0.41 \text{ s}$, the time taken for the male smash to land. The dotted line indicates the female smash trajectory after the male smash has landed $t = 0.41-0.61 \text{ s}$. The initial y position is equal (-6 m ; net = 0) and the velocity in the x -direction was 0. The coefficient of air drag acceleration (α) was calculated as 0.2152 (Shen et al., 2020), where $\alpha = \frac{1}{2} C_D \frac{\pi d^2}{4} \rho v^2$, and C_D (coefficient of drag) = 0.59 (Alam et al., 2010), d (diameter of the shuttlecock) = 0.06 m, ρ (air density) = $1.29 \text{ kg}\cdot\text{m}^{-3}$ and v is the shuttlecock velocity.

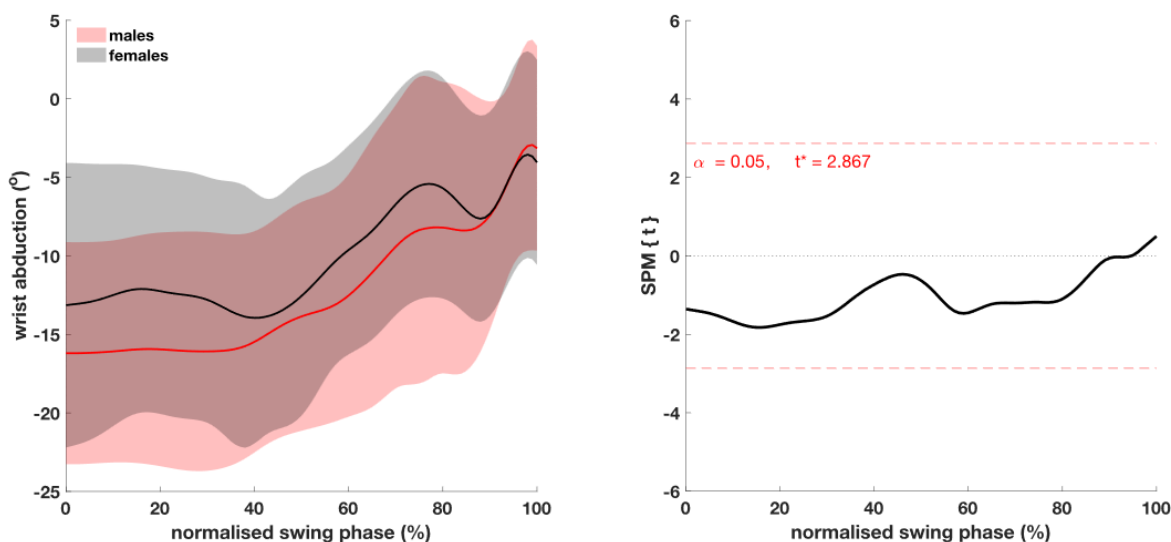


Figure 10. Wrist abduction angles during the swing phase (left), statistical parametric mapping analysis comparing males and females (right).

From a technique perspective, many of the differences between male and female players were during the backswing, approximately 0-80% of the swing phase for the majority of players. This supports previous research where players who achieve more counter-rotated positions for axial rotation of the trunk (x-factor) and pull the arm further back relative to the trunk (negative plane of elevation angle) achieve greater shuttlecock speeds (King et al., 2020; Towler, 2022). Whilst the present study did not include a specific analysis of angular velocities, given that the normalised time histories for many joint angles were similar and shorter swing duration for males (typically 28 ms shorter; 183 vs. 211 ms), it can be inferred that the average angular velocities were greater for male players.

CONCLUSIONS

This study quantifies differences in smash performance between elite male and female badminton players. On average, male players produced smash speeds 26% greater than their female counterparts and steeper trajectories, which has significant consequences for an opponent's chances and options for returning the stroke. These differences in shuttlecock speed and/or racket head speed are coupled with technique differences seen during the backswing phase, particularly in proximal joints (trunk and shoulder) which likely enhance the forward swing phase. Further research may look at intervention studies based on strength and technique improvements linked to these differences, as well as tactical strategies based on known differences in smash performance between males and females and the constraints placed upon the opponent.

AUTHOR CONTRIBUTIONS

Conceptualisation, methodology: H.T. and M.A.K.; data collection: H.T.; data processing: H.T.; formal analysis and writing—original draft preparation: H.T.; writing—review and editing: M.A.K.; supervision: M.A.K. All authors have read and agree to the published version of the manuscript.

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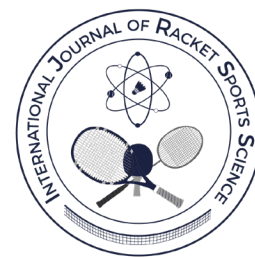
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Hearing the roar: Spectator noise and umpires stress in major badminton tournaments

Hearing the roar: Spectator noise and umpires stress in major badminton tournaments



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Abstract

This study investigates the effects of spectator noise on umpire stress levels during major badminton tournaments. Previous research has shown that spectator noise can affect performance and decision-making in sports, including badminton. However, there is limited understanding of how this phenomenon explicitly affects umpires, who play a crucial role in officiating matches. Nine experienced umpires from the 24th Badminton World Federation (BWF) World Championships participated in the study. Heart rate variability (HRV) was used to measure stress levels objectively. In addition, subjective noise sensitivity and general stress levels were assessed using validated questionnaires. Noise levels were recorded on court using stationary sound level meters, and individual noise exposure was measured using personal carried noise dosimeters. The results showed a statistically significant correlation between spectator noise level and stress, mainly when umpires were working as service judge. Umpires with a higher subjective sensitivity to noise and higher general stress levels showed a stronger correlation between noise levels and stress during matches. The findings suggest that spectator noise may be a factor to consider in efforts to support umpire performance and well-being in stressful environments. Further research is needed to investigate the potential impact of this association on decision-making processes.

Keywords: *Spectator noise, stress, badminton, umpires.*

Resumen

Este estudio investiga los efectos del ruido de los espectadores en los niveles de estrés de los árbitros durante los torneos más importantes de bádminton. Investigaciones anteriores han demostrado que el ruido de los espectadores puede afectar el rendimiento y la toma de decisiones en los deportes, incluido el bádminton. Sin embargo, no se sabe muy bien cómo afecta explícitamente este fenómeno a los árbitros, quienes desempeñan un papel crucial en el arbitraje de los partidos. En el estudio participaron nueve árbitros con amplia experiencia que estuvieron en el 24.º Campeonato Mundial Bádminton organizado por la Federación Mundial de Bádminton (BWF). Se utilizó la variabilidad de la frecuencia cardíaca (VFC) para medir objetivamente los niveles de estrés. Además, se evaluaron la sensibilidad subjetiva al ruido y los niveles generales de estrés mediante cuestionarios validados. Los niveles de ruido se registraron en el campo mediante sonómetros fijos y la exposición individual al ruido se midió con dosímetros de ruido personales. Los resultados mostraron una correlación estadísticamente significativa entre el nivel de ruido de los espectadores y el estrés, principalmente cuando los árbitros trabajaban como jueces de servicio. Los árbitros con una mayor sensibilidad subjetiva al ruido y mayores niveles generales de estrés mostraron una mayor correlación entre los niveles de ruido y el estrés durante los partidos. Los resultados sugieren que el ruido de los espectadores puede ser un factor a tener en cuenta en las iniciativas

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para apoyar el rendimiento y el bienestar de los árbitros en entornos estresantes. Es necesario seguir investigando el impacto potencial de esta asociación en los procesos de toma de decisiones.

Palabras clave: *ruido de los espectadores, estrés, bádminton, árbitro.*

BACKGROUND

Spectator noise is a common factor at most major sporting events, and spectator noise has been shown to affect the performance of athletes and technical officials in terms of performance and decision-making (Myers & Balmer, 2012; Nevill et al., 2002; F. Sors et al., 2019; Starcke & Brand, 2012; Unkelbach & Memmert, 2010).

Badminton is no exception, and high spectator noise levels are common at badminton championships (Sjodin & Fahlström, 2018). Research has shown that spectator noise can affect referees' decision-making in football (Nevill et al., 2002; Sors et al., 2021). However, the reason for this effect can vary from person to person (Nevill et al., 2017) but also that that the decisions of referees with high anxiety might be more easily influenced by external factors like spectator noise (Sors et al., 2019).

High noise levels may in itself be perceived as unpleasant and thus cause stress and secondly, especially in a sports context, make it challenging to perform the work task and thus cause stress (Burns et al., 2016; Goyal et al., 2010; Sors et al., 2019). In a sports context, with spectator noise as the primary noise source, noise exposure is also more variable and subject to less control for technical officials such as umpires. Lower control of the noise source has been shown to be associated with lower cognitive performance (Belojevic et al., 2003; Paunović et al., 2009; Sobotova et al., 2010; Wright et al., 2016).

It is also likely that the vast media and spectator interest is putting additional pressure on the technical officials at the various venues. The time they spend working in the noise is also of great importance. Longer exposure time has been shown to increase fatigue (Ackerman et al., 2010).

During high-attention work at a high level of competition, cognitive resources can become depleted. It is argued that this affective experience of exhaustion can place additional cognitive demands on the individual as they attempt to maintain attention levels. If this continues during work, performance may decline to an unacceptable level (Beal et al., 2005). This is thought to harm our ability to maintain our attention on the work task, especially if we have had fluctuations in performance during a workday. It is suggested that this may harm our ability to maintain our attention on the work task, especially if we have previously had challenging tasks during a previous workday (Trogakos & Hideg, 2009). Working with a high cognitive load, pressure from spectators,

and a high noise level that strains working memory (Baddeley, 2001) can lead to cognitive fatigue, so referees tend to make more mistakes over time (Nevill et al., 2002; Nevill et al., 2017).

The physiological explanation for the stress response due to noise is that a physical and mental imbalance caused by noise triggers a stress response to maintain homeostasis. The sympathetic nervous system becomes hyperactivated with chronic stress, leading to physical, psychological, and behavioral abnormalities. Studies have shown that noise exposure in the workplace can lead to hormonal changes through the release of cortisol (Ising & Kruppa, 2004; Ising & Prasher, 2000; MIKI et al., 1998). Measuring stress in an objective, non-intrusive way is difficult, especially in sports. As mentioned earlier, stress can be measured by taking cortisol samples, but this method is time-consuming, costly, and challenging to conduct during an activity. Questionnaires can also be used but do not measure the stress experienced during the activity. Heart rate variability (HRV) is another way to measure stress and has been used as an objective measure of stress in several studies (Jiménez Morgan & Molina Mora, 2017; Pagaduan et al., 2020).

It has been reported (Dimitriev & Saperova, 2015) that psychological stress increased predictability, regularity of RR (R waves) intervals, and reduced complexity. This reflects a shift towards more stable and periodic HR (heart rate) behavior under stress. The results of (Sim et al., 2015) showed the impact of different types of noise on HRV parameters. Reductions in HRV were observed during noise exposure: After adjusting for noise frequency, during low-frequency noise exposure, HF was reduced (a reduction of 32%, 34%, and 16%, respectively), and during high-frequency noise exposure was found to reduce LF (low frequency) by 21% compared to no noise exposure (Walker et al., 2016). The most commonly reported factor associated with variations in HRV variables was low parasympathetic activity, characterized by a decrease in the high-frequency band and an increase in the low-frequency band. Neuroimaging studies suggest that HRV may be associated with cortical regions (e.g., ventromedial prefrontal cortex) involved in stress appraisal; recent neurobiological evidence suggests that HRV is influenced by stress and supports its use for objective assessment of stress (Kim et al., 2018).

Considering the complexity of working as an umpire in badminton, which requires quick decision-making, it is interesting to investigate to what

extent spectator noise can influence the umpire's experience of stress. In badminton, the umpires have two functions during matches: the main umpire and the service judge. The main umpire sits above the court and is responsible for all decisions on and around the court. The umpire ensures that the game is played according to the badminton rules. The main umpire makes calls regarding service errors and other errors or omissions of the players. The umpire keeps the score during the match and records all incidents of misconduct. The umpire's jurisdiction extends from entering the court before the match until leaving the court after the match. The second function is the service judge, whose task is to judge the technical execution of the player's serve and to assist the main umpire in making a decision in case of uncertainty. The service judge sits on the floor next to the net to fulfill these tasks. The two different roles are of particular interest due to their difference in cognitive load during matches. There is a lack of studies investigating the effects of noise on stress, especially in a sports context, using objective data on stress levels in an ecologically valid setting.

AIM

The study aims to use HRV data from umpires at a major badminton tournament to investigate whether there is an association between audience noise and stress reactions and whether this possible association is also related to subjective noise sensitivity.

Secondly, the study also aims to investigate whether a possible association between spectator noise and stress differs depending on the officiating role (i.e., a main umpire and service umpire).

METHODS

Participants

All umpires ($n = 16$) who participated in the 24th Total Badminton World Federation (BWF) World Championship, 2020, in Basel, Switzerland, were invited to participate in this study. A total of nine umpires participated in this study (M age = 46 years, $SD = 3.9$ years). All umpires were BWF-certified, which is the highest level of umpiring. During the BWF World Championships, each umpire officiated an average of 5.2 ($SD = 2.3$) matches and 5.1 ($SD = 3.9$) as a service umpire.

Procedure

This study was conducted in collaboration with the BWF and, the ethical review board in Sweden approved the study in Sweden, dnr 2019-06424.

Prior to the BFW World Championships, all referees were informed of the study's aims by a research team member at a meeting. In particular, information about

the purpose of the study, the use of their information and data would be used, and the voluntary nature and confidentiality of the study were discussed. At this stage, participants had the opportunity to ask questions about the study before giving their consent to participate.

On the tournament's first day, all on-site umpires were on location, asked by a project team member to participate in the study, which took place over the seven days of the championships. Umpires that accepted to participate were again informed about the aim of the study. Information also included that their participation was strictly voluntary and that they could end their participation at any time without the need for an explanation. All participants were also informed that all data would be presented anonymously. All participating umpires gave their written consent to participate in the study.

The first day of the tournament was used as a pilot to test all settings on the equipment and to answer a multi-section questionnaire asking for demographic information and various health and stress-related questions (see section Questionnaires).

From the second day and throughout the tournament, all participants were fitted with heart rate variability sensors before deployment. They were required to wear them throughout their shift, including rest periods between matches. The stationary sound level meters, which measure the noise of spectators near the courts, were also put into operation before the start of the day's first match.

The time for each umpire, whether they were umpiring or serving, and the rest periods were recorded by the project group using a log.

After each work shift, all umpires removed the heart rate variability equipment and the personal noise dosimeter. The sound level measurements near the courts were also completed at the end of the day. This procedure was repeated on all days of the tournament. As only three heart rate variability devices were available, not all umpires could be monitored daily.

MEASURES

Questionnaires

All participating umpires answered a questionnaire with demographic questions concerning age, gender, and hearing-related health at the tournament's beginning. Weinstein's Noise Sensitivity Scale (NSS-11) (Weinstein, 1978) was used to measure the participants subjective sensitivity to noise. The scale is composed of 21 items addressing affective reactions and attitudes to general noise and everyday environmental sounds. For every statement, participants indicate their agreement on a 6-point likert scale, which ranges from 1(disagree strongly)

to 6 (agree strongly). Items include “Sometimes noises get on my nerves, and I get irritated” and “I am good at concentrating no matter what is going on around me”. Individual sensitivity is seen as lying on a continuum ranging from high to low. The scale has been used across several contexts and has strong psychometric properties of validity and reliability (Nordin et al., 2013).

Questions were also asked regarding their hearing status using the question, “How is your hearing?”. The participants were asked to grade their hearing using a 1-3 Likert scale ranging from 1 = Good, no problem, 2 = slightly reduced, and 3 = strongly reduced. Experience of tinnitus was also asked using the question “Do you experience tinnitus?” using the following grading 1 = No, 2 = Yes in both ears, 3 = Yes, only in the left ear, 5 = other. Participants who experienced tinnitus were also asked to rate the frequency of experiencing their tinnitus and its severity.

Subjective stress was measured using the Perceived Stress Scale 10 (PSS-10) (Cohen et al., 1983; Cohen & Williamson, 1988). The PSS-10 has been shown to have high internal reliability and good construct validity in domains such as anxiety, depression and mental or physical exhaustion (Nordin & Nordin, 2013). The questions are rated on a four-point Likert scale ranging from 0=never to 4=very often. All questions are summarized into a total score, with higher scores corresponding to higher perceived stress.

Sound level measurements

During the tournament (seven days), sound level measurements were measured between the four courts using two Class 1 stationary sound level meters (Svantek 979, Svantek 977). The sound level meters were positioned in the center between two courts each.

Both sound level meters were set to log dB(A)Leq, dB(C) peak, dB(A)max with the range set to 30 to 137 dB for Leq and 70-140 for Cpeak, 10 times per second. One-third octave band data was also collected for all measurements. The microphones compensation filters were set to diffuse field. All sound level meters were calibrated each day using a Svantek SV35A Class 1 acoustic calibrator.

The sound level measurements were started before the first match and stopped after the last match each day. Sound levels for each day were analyzed using the Svantek PC++ software. The sound level data collected were recalculated into 1-minute logging values to match the heart rate variability data.

Heart rate variability measurement

Three kits of eMotion Faros 180 model for heart rate variability were used in the present study. The kits were mounted on the participating umpires in

the morning before their first match every day of the tournament. Due to the limited number of kits available, all matches could not be measured for all umpires. The kits were evenly distributed among the participating umpires during the whole tournament. After the umpires last match of the day, the equipment was removed. If other participating umpires, not wearing a kit, had more matches the same day, the kit was mounted on that umpire to maximize the number of measurement hours.

The ECG signals were recorded (1000 Hz) offline over a defined period of time (day, hours), events (breaks, umpire-times etc.) were logged, and after review transferred to KUBIOS-HRV-Software. This is a full-featured heart-rate-variability analysis software: it was used for accurate QRS and pulse wave detection, automatic artifact correction algorithms, automatic analysis sample generation, the calculation for all commonly used time-domain, frequency-domain and nonlinear HRV analysis parameters and for time-varying.

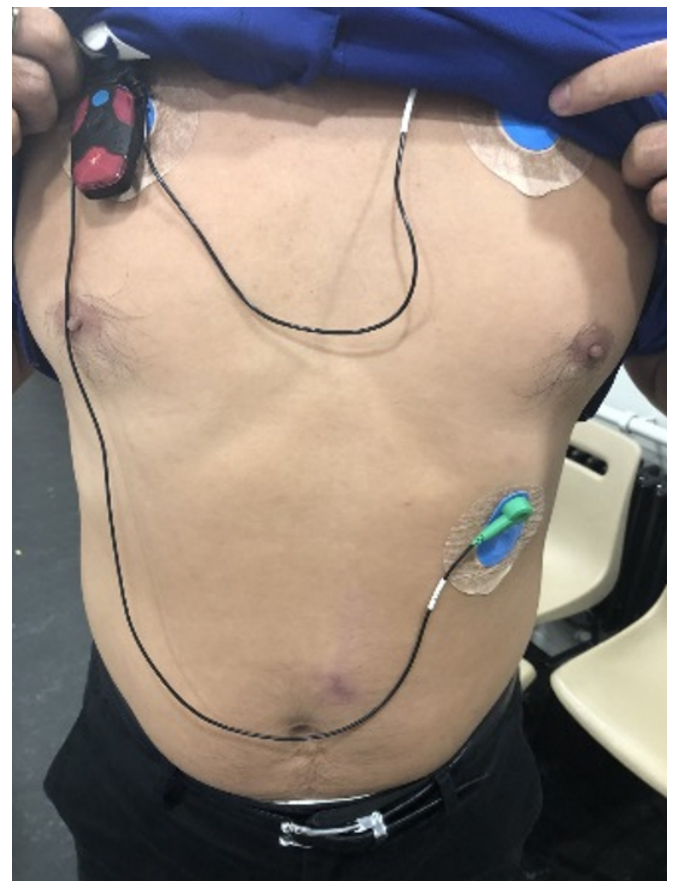


Figure 1. Positioning of the ECG-electrodes and the recorder on the trunk

STATISTICAL ANALYSES

All analyses were made using the Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows, Version 28.0; Armonk, NY). All correlations were analyzed using Pearson's correlation coefficient with the level of significance set to α 0.01. Differences

in correlation strengths were analyzed using Fischer's R to Z transformation. The stress variable as well as all noise level variables were analyzed for kurtosis and skewness. Range range for kurtosis varied between .57 to -.06, and for skewness .55 to -.41. The data was assessed as normally distributed. Non parametric tests were used to analyze the subjective reported data that was not normally distributed.

RESULTS

In [Table 1](#) are the descriptive data regarding heart rate variability data (PNS = parasympathetic nervous system, SNS = Sympathetic nervous system, Stress = software calculation generating a stress value based on the relation between PNS and SNS) as well as the subjective noise sensitivity (NSS-11) and subjective stress (PSS-10) presented.

The correlations in [Table 2](#) show that there is a statistically significant correlation between measured stress using heart rate variability and LafMax (A weighted maximum sound level) and when working as an umpire $r(1314) = .08$, $p = .006$ and as a service umpire $r(1058) = 0.27$, $p = .001$. A similar result was also observed regarding dBA_{Leq} (A weighted equivalent sound level) and stress when working as an umpire $r(1314) = .17$, $p = .001$, and stress when working as a service umpire $r(1058) = .029$, $p = .001$. A statistically significant correlation was also observed for stress and C_{peak} (C weighted impulse sound) when working as a service umpire $r(1058) = .023$, $p = .001$. However, no statistically significant correlation was observed for C_{peak} when working as an umpire.

Table 1
Heart rate variability data and subjective noise sensitivity and stress.

	N	M	SD
PNS	1314	-21963.0	9135.2
SNS	1313	34823.4	16822.8
Stress	1316	162465.6	53349.8
NSS-11	7	35.1	8.4
PSS-10	7	13.7	3.0

Table 2
Correlations for stress (value and stationary sound levels when working as umpire and service umpire

	Laf_{Max}		dBA_{Leq}		C_{peak}
Stress umpire	0.08	**	0.17	**	0.04
Stress service umpire	0.28	**	0.25	**	0.23 **

The difference in strengths of the correlations for umpires and service umpires was tested using Fischer's r to z transform the R values, presented in [Table 2](#). By comparing the Z scores, the analyses revealed that there is a statistical difference, $P <$

.05, for Laf_{Max}, $Z_{observed} = -4.8$, dBA_{Leq}, $Z_{observed} = -3.1$, and C_{peak}, $Z_{observed} = -3.5$ between the two groups. The results show that when working as a service umpire, there is a stronger association between noise levels and stress than when working as an umpire.

Correlations at an individual level for working as an umpire or a service umpire are presented in [Table 3](#). As can be observed, some individuals, especially when working as a service umpire, show a stronger correlation between noise levels and stress. As can be observed for Umpire 1, the stress levels increased when exposed to higher LafMax noise levels as well as equivalent dBA noise levels when working as a service umpire. A similar result was observed for Umpire 5. Umpire 4 showed no statistically significant correlations between noise and stress levels.

Table 3
Correlations for stress value and stationary sound levels when working as Umpire and Service umpire at for Umpire 1 to 9

		Laf_{Max}		dBA_{Leq}		C_{peak}
Umpire 1	Stress Umpire	0.05		0.18	**	0.01
	Stress Service Umpire	0.27	**	0.29	**	0.08
Umpire 2	Stress Umpire	0.10		0.18		0.03
	Stress Service Umpire	-0.15		-0.29	*	0.13
Umpire 3	Stress Umpire	-0.14	*	0.00		-0.07
	Stress Service Umpire	0.12	*	0.10		-0.01
Umpire 4	Stress Umpire	-0.07		0.00		0.04
	Stress Service Umpire	0.05		0.20		-0.28
Umpire 5	Stress Umpire	0.17	**	0.27	**	-0.06
	Stress Service Umpire	0.07		0.22	**	0.11
Umpire 6	Stress Umpire	-0.09		-0.14		-0.21
	Stress Service Umpire	-0.10		-0.26		0.02
Umpire 7	Stress Umpire	-0.11		0.37	**	-0.10
	Stress Service Umpire	0.07		-0.18	*	0.23 **
Umpire 8	Stress Umpire	0.24	*	0.06		0.08
	Stress Service Umpire	n/a		n/a		n/a
Umpire 9	Stress Umpire	0.00		0.04		0.05
	Stress Service Umpire	-0.02		0.30	**	0.03

* Correlation is significant at the 0.05 level

** Correlation is significant at the 0.01 level

Based on the individual results in [Table 2](#), a Mann-Whitney U test was used to analyze whether umpires have an association between noise exposure (dBA_{Leq}) and stress (HRV) during matches working as a service umpire (Umpire 1, 2, 5, 7, 9) differed regarding their rated noise sensitivity and general stress different

compared to umpires (Umpire 4, 6) not having this association. Noise sensitivity data is missing for umpire 3 and 8. Umpires with an association between noise and stress during matches reported higher subjective noise sensitive ($Mdn = 36.0, n = 5$) compared to the non-association group ($Md = 27.5, n = 2$), $U = 3.5, z = -0.61, p >.05$, however; the difference was not statistically significant.

When comparing the same groups regarding general experienced stress, the results showed that umpires with an association also reported their general stress as higher ($Mdn = 15.0, n = 5$) compared to the non-association group ($Mdn=11.5, n = 2$), $U = 1.5, z = -1.37, p >.05$, however; the difference was not statistically significant.

DISCUSSION

The aim of this study was to investigate whether there is an association between spectator noise during matches in a major badminton tournament and stress in the form of heart rate variability changes among the umpires. The results indicate a weak to moderate correlation between spectator noise and stress during matches for some umpires during the tournament studied.

The result of the present study suggests that the association between noise and stress was stronger when the umpires worked as service umpires compared to umpiring. A result that may be explained by the difference in cognitive load and stress, as umpires have to give their full attention throughout the match, while the service umpire focuses mainly on the players' serve. Since more decisions have to be made during a match, the stress level is likely to be higher according to most physiological stress theories, such as Lazarus' transactional stress model (Lazarus, 1966) and McEvans' model of allostatic load (Juster et al., 2010). For most participating umpires, it is likely that the stress level when umpiring may have reached levels that spectator noise cannot further influence the often-called ceiling effect.

This study did not investigate whether the association between noise and stress found in this study has a negative or positive impact on the umpire's decision-making. The increased stress due to spectator noise likely has a positive effect on some umpires' decision-making and a negative effect on others. Research suggests that the effects of stress on decision-making follow a U-curve, where too little or too much stress can lead to underperformance in correct decision-making (Starcke & Brand, 2012), and this most likely varies from person to person. Therefore, the individual differences observed in the present study are of particular interest. When controlling for self-reported general noise sensitivity and self-reported general stress, the results showed that the umpires who showed a stronger association

between noise and stress during matches also reported being more sensitive to noise in general and reporting higher general stress levels. This group difference was not statistically significant, probably due to the limited number of participants in this study. The result shows that umpires who enter the court with a subjective sensitivity to noise are also more stressed during matches when working as service umpires. The results of the current study are consistent with previous studies (Nordin et al., 2013), showing that individuals with higher noise sensitivity are often associated with higher stress levels. Individuals with higher noise sensitivity have also been shown to be more impaired by noise, both in terms of overall performance and in mental tasks during noise exposure (Glass et al., 1973; Miedema & Vos, 2003). The results of this study have shown that some umpires are more affected by noise than others, which in turn may affect their performance during matches. The implications of these findings and the extent to which this may affect decision-making and performance need to be investigated in future studies.

Due to the limited number of participants in the present study, the results should be interpreted cautiously. Therefore, the statistical analyses of the subjectively reported data were not statistically significant. Furthermore, the correlation analyses were mostly weak to moderate and the actual psychological experience of this noise-induced change in stress level needs further investigation. The study does also not take into account that other variables such as actions on or off court may affect the stress level.

CONCLUSIONS

In conclusion, this study shows that umpires heart rate variability and stress can be affected by noise levels during badminton matches at major tournaments. The effects vary from person to person and from work tasks, and therefore, spectator noise must be considered as a factor that can affect the umpire's performance during matches. Noise is probably only one of many factors that can affect stress levels; further studies are needed in this area of research.

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