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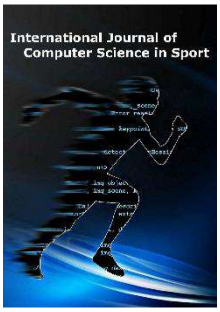

Estimating the Relevance of First Offensive Shot Tactics in Table Tennis via Simulation Based on a Finite Markov Chain Model

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Abstract

Finite Markov chain modelling is a commonly used type of stochastic modelling employed in performance analysis of net games. Finite Markov chains are based on a state transition model which can be used to depict the game structure of net games as a succession of states which are defined as equivalence classes for game situations, e.g. service and return. Furthermore, the theory of finite Markov chains allows for the calculation of model variables which are of significant interest not only for validation but also for performance analysis, like wining probabilities or expected rally lengths starting from different states. By simulation, of a more-or-less of tactical behaviors one may study the impact of these tactics on overall success. A novel state transition model for table tennis is introduced in this study as extension of an existing model in the literature containing only the first offensive shot. The new model additionally contains subsequent shots since they may be perceived as being influenced by the first offensive shot. A sample of 105 single matches (49 female, 56 male) at the 2020 Tokyo Olympics was examined. The validation of the Markov property resulted in satisfactory results. The relevance of 26 transitions denoting specific tactical behaviors was obtained using simulation and subsequently compared between sexes. Results provide insights concerning the game structure of table tennis with a particular emphasis on the transition from the initial phase of rallies to the first offensive shot.

KEYWORDS: TABLE TENNIS, MARKOV-CHAIN MODELLING, VALIDATION.

Introduction

Finding adequate structural representations for game sports can be seen as a key challenge in theoretical performance analysis and sports informatics. This is due to their inherently complex nature and the corresponding difficulty of quantifying performance in this context (Lames, 2023). Game sports are determined by variant, dynamic and context dependent tactical behavior of the interacting players or teams (Lames & McGarry, 2007; Sampaio & Leite, 2013). These properties lead to the notion of game sports as dynamical interaction processes with emergent behavior (Lames, 2023) and substantiate the need to find adequate methods to quantify sports performance (McGarry, 2009).

The most common metrics for quantifying game sports performance are arguably performance indicators. In game sports, performance indicators largely represent absolute or relative frequencies of actions obtained through notational analysis. In discrete form, performance indicators therefore capture individual aspects of tactical behavior during a match (Hughes & Bartlett, 2002). In a broader context, performance indicators are also used with the aim of identifying specific playing characteristics in players or teams depicted as performance profiles (Hughes, Evans, & Wells, 2001; O'Donoghue, 2005). Considering the inherent structural properties of game sports which are defined by variant tactical behavior, this form of quantifying performance warrants conceptual objections. In all of the described forms, performance indicators omit the context of captured tactical behaviors as they neglect the underlying sequence of events leading to those tactical behaviors as well as interactions with the opponent (Lames & McGarry, 2007; Sampaio & Leite, 2013). Moreover, this poses the issue of identifying the relationship between tactical behavior and outcomes (McGarry, 2009).

As a consequence, finding more adequate model representations for game sports is crucial to account for their inherent characteristics and to provide a comprehensive understanding of game structure (Lames, 2023). To that end, importing models from other fields to performance analysis has yielded promising results in the past. For an application in theoretical performance analysis of game sports there are however several factors which should be taken into consideration. Two crucial properties required in this context are a model's adaptability to a sports context as well as the possibility for empirical and structural validation (Lames, 2023). Both properties have arguably been demonstrated for finite Markov chain modelling in a variety of applications, especially in net games.

Markov chains represent a form of stochastic modelling, where a process is modelled as a sequence of states. These states represent equivalence classes for certain elements of the process (Kemeny & Snell, 1976; Lames, 2020). The process moves forward through transitions between states. A transition matrix comprised of these states consists of the empirical transition probabilities between the states and is typically a very informative representation of the process as a whole. Assuming the Markov property, which is a prerequisite for simulations, requires that a transition to a subsequent state only depends on the present state of the process (Kemeny & Snell, 1976; Lames, 2020). Furthermore, in finite Markov chains the number of states and transitions is limited. Frequently, finite Markov chains include one or more absorbing states which represent the end point of the modelled process (Kemeny & Snell, 1976; Lames, 2020).

In performance analysis, these properties allow to capture the structure of game sports based on the underlying sequence of actions. This is especially applicable to net games due their clear sequence of alternating shots with each taking place in a stroke class i.e. in a state (Lames, 2020). A transition matrix of a match in a net game represents the whole match as a "super-rally" with the starting state service and absorbing states point or error. The specific value for performance analysis lies in the transitions between states as they can then be viewed as equivalent to certain tactical behaviors. This is specifically true for the transitions to absorbing states "point" and “error” that terminate a rally and are decisive shots in net games (Lames, 2020).

Finite Markov chains in the context of performance analysis have been used for a variety of applications. An early application can be found in Pfeifer and Deutsch (1981) and Parlebas (1985) for the assessment of scoring systems in volleyball. Newton and Aslam (2009) used a Markov chain Monte Carlo Method to predict match winners in Tennis. Other applications focused on the evaluation of player and team performances. Galeano et al. (2022) for instance evaluated player performances in badminton based on a Markov chain model which incorporates different playing patterns associated to playing styles. Kolbush and Sokol (2017) used a logistic regression / Markov chain model to evaluate team performance in American football based on match outcomes. Furthermore, various publications focused on specific tactical aspects. For example Liu et al. (2022) analyzed attacking patterns of different playing styles in football (soccer) using a Markov chain model based on field zones. Likewise, Marino et al. (2023) examined the emergence of critical incidences and their association with different tactical actions in Rugby union matches. Lames (1991) introduced the concept of simulating changes in tactical behavior by manipulating associated state transitions to determine the relevance to overall match performance in net games. This early model was improved and adapted to modern tennis by Rothe and Lames (2023). In table tennis specifically, Pfeiffer, Zhang, and Hohmann (2010) used this concept to examine the relevance of different shot techniques.

The simulative approach of determining the relevance of tactical behaviors under assumption of the Markov property is described in detail in the method section. In principle, by simulating changes in the frequency of certain state transitions in the general transition matrix it is possible to calculate the impact of these changes on the overall point winning probability. The impact on overall point winning probability is subsequently used as a metric to quantify the relevance of underlying tactical behaviors in a match or the game structure in general (Lames, 2020). This method may thereby provide insights to relevant aspects of theoretical and practical performance analysis like the structure of performance or tactical behaviors which should be considered as priority targets for training.

This paper uses the approach introduced by Lames (1991) for tennis with a novel state transition system which was adapted to table tennis, emphasizing the initial transition between defensive and offensive play. The state transition system which serves as a basis for finite Markov chain modelling incorporates the concept of first offensive shots (FOS) introduced by Fuchs and Lames (2021). In table tennis, first offensive shots refer to the first shot after the service which is played without backspin (Fuchs & Lames, 2021). Therefore, the FOS serves as a turning point in the rally where an initial transition from defensive backspin shots to offensive shots (e.g. top spin or flip) occurs. Further, Fuchs and Lames (2021) found unique properties in the shots immediately following the FOS, which is also emphasized in the novel state transition model for table tennis.

The aim of the present study was to examine table tennis tactical behavior using a novel state transition model in the form of a finite Markov chain. Before doing so the assumption of the Markov property has to be validated which is done here by comparing predicted winning rates assuming the Markov property with observed ones. This allows leveraging the theory of finite Markov chains by conducting simulations resulting in estimates for the relevance of individual tactical behaviors. Furthermore, we provide descriptive statistics on the relevance of several tactical behaviors specifically regarding the FOS and compare both sexes to infer possible differences in tactical behavior between male and female players.

Methods

Data Acquisition and Sample

Notational data was acquired within the scope of a bachelor thesis (Wiesener, 2022)[1] by systematic game observation with individual strokes being the unit of observation and stroke types constituting the attribute of observation (Lames, 1994, p. 48). It was differentiated between service, defensive shots, first offensive shots, the three shots following the first offensive shot and the finishing part of the rally, given a rally has more than at least five shots. Additionally, the number of shots of the server and FOS player in each rally was noted as well as the winner of each rally and the player who played the FOS. The definition of the individual shot types is further detailed in the section describing the state transition model.

Subsequently the observer agreement was checked by testing inter-rater-reliability between the original observation and an observation performed by an experienced table tennis match analyst. For this purpose, a sub-sample of four 7-set matches was analyzed. Cohens Kappa coefficients were calculated for observer agreement regarding the variables server ($\kappa = 1$), rally length ($\kappa = .972$), FOS number ($\kappa = .988$), FOS player ($\kappa = .998$) and winner of the rally ($\kappa = 1$).

In total 105 matches form the men's and women's single competition of the 2020 Olympic games in Tokyo were analyzed. For that purpose, video recordings form the broadcasted matches of the TV Station "Eurosport" were used. The sample includes matches starting from the round of 128 up to the finals. The sample includes 49 women's single matches and 56 men's single matches. All players in the included matches exhibited an offensive playing style as the concept of FOS is not applicable to players using a defensive playing style (Fuchs & Lames, 2021).

State Transition Model

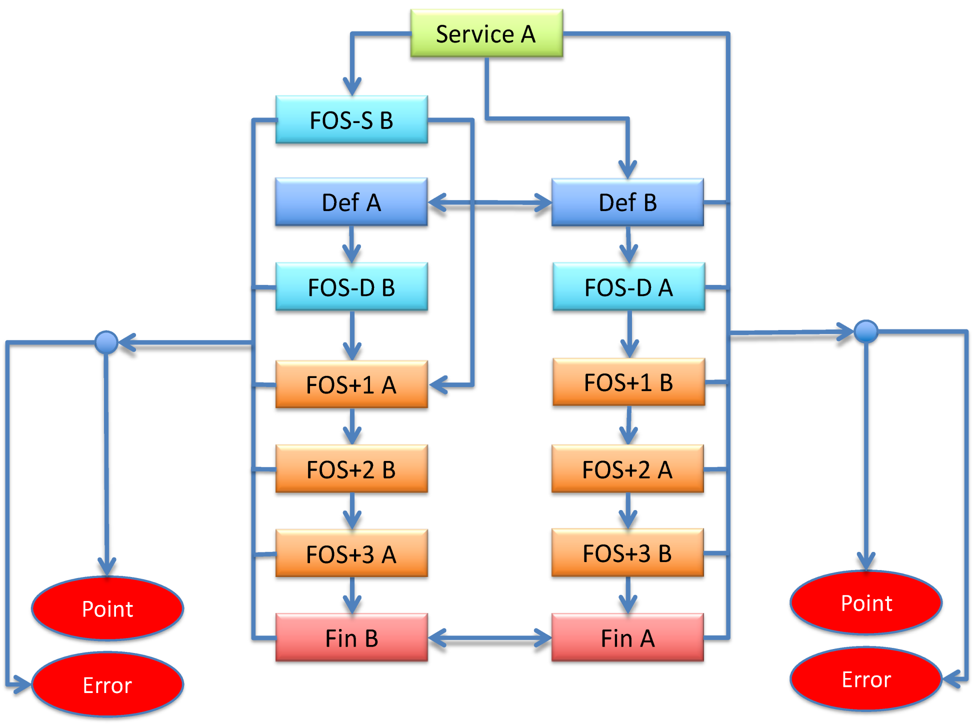

Figure 1. Flow chart of the state transition model exemplified on a rally starting with service for player A.

[1] We thank Florian Wiesener for providing the data base for this study.

Generally, a state transition model serves as procedural representation of a real-world process as sequence of states. Individual states are defined as equivalence classes for discrete elements within the given process (Lames, 2020). Thus, in the context of table tennis, a state represents a group of shots sharing similar properties. Accordingly, shots assigned to the same state are similar in terms of technique and their tactical role during the rally. Further, transitions are possible between different states based on their occurrence and frequency in the modelled real live process (Lames, 2020).

A flow chart representation of the utilized state transition model for table tennis is given in Figure 1.

The state transition model in this case formally represents a finite Markov chain or more specifically its associated state space. Therefore, the number of possible transitions in the process is limited, thus accurately representing the characteristics of an actual rally (Lames, 2020). Additionally, this implies the differentiation of three state types: a starting state, transient or sets of transient states and absorbing states. The starting state and the absorbing states represent the start point and the endpoints of the modelled process. Transient states or transient sets of states respectively, make up all intermediary states. After a transient state or set of transient is left the process cannot return to it again (Lames, 2020).

State transitions refer to the transition between different equivalence classes representing specific shot types or endpoints of the rally. A state transition to a subsequent state may only occur if the specific shot sequence can be observed during the actual match. Thus, the resulting transition probabilities are derived from the observed relative frequency of shots during a match. Accordingly, a state transition is equivalent to the ball travelling between two individual shots or before a point or an error.

The process always begins in the starting state represented by the service (Service) in the present model. From the service the process may either transition to a defensive shot (Def) or a first offensive shot (FOS). The definitions for both states were derived from Fuchs and Lames (2021). Accordingly, defensive shots are defined as shots played with backspin/side-backspin typically played over the table. The first offensive shot is defined as the first shot after the service which is played without the involvement of any backspin/side-backspin, i.e. for example top spin or flip. This represents an important tactical decision, where a player either decides to take risk immediately and attack the opponent or to play more defensive and accept to possibly be put under pressure by the opponent (Fuchs & Lames, 2021).

If a defensive shot is played following the serve the process can subsequently either transit to another defensive shot or to a first offensive shot. To that end, it was decided to differentiate between two types of first offensive shots depending on if they are played following a serve (FOS-S) or later on in the rally following a defensive shot (FOS-D). This is based on the observation that both shot types differ in their difficulty with FOSs following a service appearing to be more difficult and involving higher risk for the FOS player (Fuchs & Lames, 2021). Until a FOS is played, the process remains in the state Def.

After playing a FOS, state transitions are possible to the subsequent FOS+ states which exhibit distinct characteristics, setting them apart from the initial defensive state. The three shots following the FOS are assigned to specific equivalence classes FOS+1, FOS+2 and FOS+3. FOS+2 is executed by the FOS player, while FOS+1 and FOS+3 are played by the non-FOS player. This state design was chosen to account for the advantage of the FOS player during the three shots following the FOS (Fuchs & Lames, 2021) as well as to examine the influence of the FOS in subsequent shots. Shots after FOS+3, where the advantage caused by the FOS is assumed to be no longer present, are assigned to the state representing the finishing part of the rally (Fin).

Regarding formal aspects of finite Markov chains this additionally accounts for the chain property which demands a certain invariance of the process (Lames, 2020).

All the aforementioned states following the serve represent transient states (FOS, FOS+1, FOS+2 and FOS+3) or sets of transient states (Def and Fin). Transitions to an absorbing state are possible from the starting state as well as all transient states in the process. In terms of a table tennis rally those states are equivalent to point and error. Points in this context are seen as equivalent to winners where the receiving player is not able to play a follow up shot.

Simulations Using Finite Markov Chains

Finite Markov chains represent a stochastic process in which the transition to a subsequent state may only depend on the present state. This property is termed Markov property (Kemeny & Snell, 1976). Moreover, the theory of finite Markov chains allows for a series of calculations based on an initial state transition matrix which can be of value for performance analysis (Lames, 1991). Specifically, this allows to approximate the number of steps from any state to an absorbing state as well as the absorption probability from each state. In terms of a model for table tennis this is especially interesting concerning the state serve as the approximated steps until absorption as well as the absorption probability can be viewed as equivalent to the overall rally length and probability of winning a point. For a more detailed description of the calculation steps in finite Markov chain modelling also see Lames (2020) as well as Rothe and Lames (2022).

Using the theory of finite Markov chains (Kemeny & Snell, 1976), Lames (1991) introduced the concept of determining the relevance of tactical behaviors in terms of performance by simulating changes in associated state transitions. Simulating a change in a selected state transition by deflecting the corresponding transition probability results in a modification of the modelled point winning probability. The resulting difference between the original and the modified winning probability from the state serve is subsequently used to quantify the impact of the simulated change in tactical behavior. This percentage difference of point winning probability is referred to as performance relevance.

The induced change in transition probability is always calculated proportionally to the initial transition probability. This is to account for the varying difficulty of changing tactical behaviors reflected by the simulations thereby also providing comparability between the resulting performance relevance. Given the example in Figure 2 it seems reasonable to assume that increasing the transition probability from Def to Def is less difficult than increasing the transition probability between FOS and point. To that end Lames (1991) suggested a formula for the proportional deflection of transition probabilities:

$$\Delta \mathrm{p}_{i,j} = K + 4B * p_{i,j} * \left(1 - p_{i,j}\right)$$

Here, K and B represent constants. These constants were determined in a way that the level of correlation between the initial transition probability $p_{i,j}$ and the calculated performance relevance are as minimal as possible (Lames, 1991). K stands for a constant deflection that is applied even when $p_{i,j}$ is 0 or 1 and is set applying the mentioned criterion to 0.01. B stands for the part of the deflection that is proportional to $p_{i,j}$ as one may assume that it is easier to change a transition probability in the middle of the distribution compared to very low or high ones that "feel" the unsurmountable barriers of 0 and 1. To respect these boundaries for simulation purposes, original transition probabilities $<$ 50% are deflected upwards and transition probabilities of $\geq$ 50% downwards.

Additionally, deflecting a transition probability needs to be compensated to preserve the sum of 1 for all transition probabilities of this state. This is done here according to a suggestion of Lames

(1991) with a compensation proportional to the size of the transition probability to be compensated (p_{comp}) as this compensation is not connected to a substantial tactical assumption:

$$\Delta \mathrm{p}_{comp} = \left(p_{comp}/\left(1 - p_{i,j}\right)\right) * \Delta \mathrm{p}_{i,j}$$

Figure 2 depicts the calculation of the performance relevance for the transition between the states FOSA-S and error. The transition probabilities of all remaining state transitions from this state are compensated as previously specified. Below, the resulting winning probabilities for the original as well as the simulated transition probability are given. This results in a performance relevance of -1.55 %

Lin (A)	DEF B	FOS B - S	FOS B - D	FOS+1 B	FOS+2 B	FOS+3 B	Fin B	Point A	Point B
Service A	55.22	41.79						0.00	2.99
DEF A	57.14		42.86					0.00	0.00
FOS A - S				~~75.00~~				~~6.82~~	~~18.18~~
↓				↓				↓	↓
FOS A - S*				71.36				6.49	22.16
FOS A - D				66.67				6.67	26.67
FOS+1 A					59.38			9.38	31.25
FOS+2 A						60.00		6.67	33.33
FOS+3 A							50.00	16.67	33.33
Fin A							64.71	5.88	29.41

Winning probability simulated TP	→	47.27
Winning probability original TP	→	48.82
Performance Relevance	→	-1.55

Figure 2. Example of a simulated change of the transition probability (%) between FOSA-S – Point B (Error) as well as the resulting winning probabilities (%) from the bronze medal match Lin vs Ovtcharov.

Model Validation

As mentioned in the forgoing paragraph finite Markov chains are subject to the Markov property. Therefore, the usage of all described calculations leveraging the theory of finite Markov chains likewise is based on the assumption of the Markov property thereby necessitating a validation of this property (Lames, 2020; Pfeiffer et al., 2010).

For that purpose, predictive validity has been referred to as an adequate mean to demonstrate whether the assumption of the Markov property is warranted (Lames, 2020; Pfeiffer et al., 2010). This was assessed by examining the concurrency of calculated values assuming the Markov property for winning probability as well as rally lengths with their empirically observed counterparts in all matches of the sample. Concurrency of these values was tested using Pearson's correlation. While for calculating performance relevance only the overall winning probability i.e. the winning probability starting with state serve is used, content validity was also tested for all remaining states to demonstrate the general validity of the utilized state transition model.

Statistical Testing

To assess differences in game structure between male and female players the performance relevance of all examined state transition was compared concerning the factor sex. Since data for various state transition exhibited a non-gaussian distribution a non-parametric Mann Whitney U Test was chosen for testing. The significance level was set to $\alpha = 0.05$.

Results

Model Validation

Correlations between calculated and observed point winning probability and rally length from every state were obtained to verify the assumption of the Markov property. Resulting correlation coefficients ranged from $r_{cc} = .85$ to $r_{cc} = .95$ for point winning probability and $r_{cc} = .82$ to $r_{cc} = .97$ for rally length. Overall point winning probability (winning probability starting from serve) exhibited a correlation coefficient of $r_{cc} = .91$. Total rally length (rally length starting form serve) exhibited a correlation coefficient of $r_{cc} = .96$.

Transition Matrix of a Single Match

Fan (A)	DEF B	FOS B - S	FOS B - D	FOS+1 B	FOS+2 B	FOS+3 B	Fin B	Point A	Point B
Service A	89.09	10.91						0.00	0.00
Def A	48.21		51.79					0.00	0.00
FOS A - S				78.38				10.81	10.81
FOS A - D				75.00				6.25	18.75
FOS+1 A					57.14			10.71	32.14
FOS+2 A						61.11		5.56	33.33
FOS+3 A							80.00	10.00	10.00
Fin A							67.39	6.52	26.09

Ma (B)	DEF A	FOS A - S	FOS A - D	FOS+1 A	FOS+2 A	FOS+3 A	Fin A	Point B	Point A
Service B	28.30	69.81						0.00	1.89
Def B	53.95		42.11					0.00	3.95
FOS B - S				100.00				0.00	0.00
FOS B - D				75.86				10.34	13.79
FOS+1 B					67.92			7.55	24.53
FOS+2 B						62.50		6.25	31.25
FOS+3 B							81.82	0.00	18.18
Fin B							71.79	12.82	15.38

Figure 3 Transition matrix for the men's final of the Tokyo Olympics 2020 between Fan Zhendong and Ma Long (4-11, 12-10, 8-11, 9-11, 11-3, 7-11).

Figure 3 depicts an exemplary state transition matrix of the men's competition final at the Tokyo Olympics between Fan Zhendong and Ma Long, (4-11, 12-10, 8-11, 9-11, 11-3, 7-11). Note that in this case the regular transition matrix is split in two sperate matrices for the shots of the individual players. Generally, transitions matrices of individual matches allow to identify advantages and disadvantages in certain states as well as preferences in shot selection. It is possible to identify strengths and weaknesses at the given level of abstraction, i.e. transition rates.

When looking at the transition matrix presented in Figure 3 it is apparent that both players exhibit different shot selections and tactical behavior in terms of playing their FOS. Looking at the state transition Serve-FOS-S it becomes apparent that Fan tries to attack Ma's serve in most cases

(69.81 %) while Ma largely choses to play a defensive shot following Fan's serve (89.09 %). In contrast to that, Ma attacks a larger proportion of defensive shots than Fan (51.79 % vs. 42.11 %), however the difference is much less pronounced than in the state transition Serve-FOS-S.

Further, Fan seems to take higher risk in both FOS states indicated by higher transition probabilities to errors in both states (10.81 % and 18.75 % vs. 0 % and 13.79 %). Ma on the other hand shows different tactical behavior when playing a FOS following a serve compared to after a defensive shot. When playing a FOS following his opponent's service, he chooses a rather defensive approach allowing his opponent to play a follow up shot (FOS+1) in all cases. For FOSs following a defensive shots Ma's tactical behavior is much more similar to Fan's exhibiting a comparable transition probability in the transition from FOS-D to FOS+1 (75 % vs. 75.81 %).

In the state FOS+1, which represents the shot immediately following an FOS, Ma seems to be more successful in defending his opponent's FOS with a considerably lower error rate (24.53 % vs. 32.14 %) and higher transition probability to the subsequent state (67.92 % vs. 57.14 %). Transition probabilities from FOS+2 and FOS+3 are comparable in both players.

In longer rallies Ma clearly has an advantage over Fan in this particular match indicated by a higher point and lower error rate when compared to Fan (12.82 % and 15.38 % vs. 6.52 % and 26.09 %). Likewise, Ma generally exhibits lower error rates in all states when compared to Fan.

Performance Relevance

Table 1 shows descriptive statistics of the calculated performance relevance of all state transitions in male and female players. Statistics include mean, median, minimum, and maximum values as well as the standard deviation. Statistically significant differences in terms of sex are marked by an asterisk. Furthermore, to allow for better comparison between different state transitions the magnitude of performance relevance is referred to in relation to its absolute value.

Generally, male and female players exhibit comparable performance relevancies in a majority of states. Only the state transitions Serve-Def, Def-Def and Fin-Fin exhibit statistically significant differences in terms of sex. Here the performance relevance of Serve-Def and Def-Def is higher in male players while the performance relevance of Fin-Fin is higher in female players.

For the state serve, the transition to the subsequent state FOS-S likewise exhibits a certain degree of dissimilarity in terms of performance relevance, when comparing male and female players, with a higher performance relevance in male players, although this difference is not statistically significant. For the state Def male and female players show opposing trends in terms of performance relevance. In male players the transition to a subsequent shot in Def exhibits higher performance relevance than the transitions to FOS-D while in female players the opposite is the case. However, the difference in the transition Def-FOS-D is less pronounced.

Transitions from both FOS states to the subsequent state FOS+1 exhibit comparable performance relevancies in male and female players. The subsequent state transitions FOS+1-FOS+2, FOS+2-FOS+3 and FOS+3-Fin again exhibit comparable performance relevancies with slightly higher values in female players.

In general, state transitions to point and error are largely comparable between male and female players with a greater difference being present only in the transition Fin-Error. Here female players exhibit a higher performance relevance than male players, although this difference is not statistically significant.

Table 1. Descriptive statistics of the performance relevance per state transition.

State Transitions	Mean		Median		Max.		Min.		Std.	
	m	w	m	w	m	w	m	w	m	w
Serve-Def *	0.32	0.13	0.27	0.08	2.12	1.59	-1.08	-1.34	0.60	0.58
Serve-FOS-S	-0.22	-0.06	-0.18	-0.05	1.56	1.61	-2.12	-1.54	0.65	0.57
Serve-P	0.56	0.55	0.52	0.53	1.45	1.60	0.24	0.22	0.18	0.20
Serve-E	-0.67	-0.66	-0.62	-0.59	-0.24	-0.30	-1.71	-1.57	0.23	0.24
Def-Def *	0.44	0.25	0.37	0.19	2.64	1.31	-0.71	-0.55	0.49	0.33
Def-FOS-D	0.12	0.24	0.08	0.20	1.40	1.62	-1.27	-1.63	0.49	0.56
Def-P	0.52	0.51	0.49	0.46	1.81	1.24	0.16	0.04	0.24	0.25
Def-E	-0.91	-0.87	-0.84	-0.80	-0.12	-0.04	-2.17	-2.18	0.39	0.46
FOS-S-FOS+1	0.82	0.85	0.77	0.88	2.27	2.72	-0.31	-0.35	0.54	0.54
FOS-S-P	0.43	0.39	0.36	0.34	1.33	1.46	0.01	0.04	0.29	0.27
FOS-S-E	-1.11	-1.07	-1.09	-1.02	-0.06	-0.04	-2.62	-2.72	0.55	0.55
FOS-D-FOS+1	0.61	0.66	0.55	0.66	2.01	1.91	-0.81	-0.52	0.56	0.52
FOS-D-P	0.54	0.46	0.52	0.41	1.30	1.20	0.06	0.06	0.32	0.28
FOS-D-E	-1.07	-1.01	-1.02	-1.02	-0.09	-0.12	-2.45	-2.01	0.49	0.50
FOS+1-FOS+2	1.53	1.62	1.48	1.58	3.17	3.69	-0.24	0.15	0.72	0.73
FOS+1-P	0.90	0.82	0.85	0.71	2.69	1.96	0.04	0.20	0.47	0.40
FOS+1-E	-2.12	-2.13	-2.07	-2.10	-0.35	-0.62	-4.07	-4.02	0.76	0.75
FOS+2-FOS+3	0.77	0.89	0.69	0.85	2.66	2.06	-0.57	-0.13	0.53	0.46
FOS+2-P	0.46	0.45	0.43	0.38	1.55	1.30	0.04	0.03	0.27	0.29
FOS+2-E	-1.07	-1.15	-1.03	-1.12	-0.04	-0.16	-2.87	-2.49	0.50	0.53
FOS+3-Off	0.50	0.58	0.48	0.55	1.56	1.48	-0.44	-0.29	0.37	0.41
FOS+3-P	0.32	0.31	0.29	0.25	1.06	1.20	0.01	0.02	0.23	0.24
FOS+3-E	-0.72	-0.78	-0.67	-0.67	-0.02	0.00	-1.88	-2.00	0.42	0.43
Fin-Fin *	1.10	1.31	0.99	1.20	3.58	3.59	0.08	0.00	0.66	0.74
Fin-P	0.66	0.65	0.60	0.52	2.07	1.78	0.03	0.00	0.43	0.48
Fin-E	-1.51	-1.66	-1.31	-1.58	-0.27	0.00	-4.05	-4.24	0.78	0.97

Figures 3 shows the performance relevancies of state transitions from both FOS states as well as all subsequent states to the following transient state and error. Evidently error rates exhibit a comparatively higher performance relevance as transitions to transient states. Here all error rates apart from the error rate in FOS+3 exhibited performance relevancies greater than 1%. Regarding transitions to subsequent transient states specifically, the transitions FOS+1-FOS+2 as well as Fin-Fin exhibit comparatively high performance relevance.

Overall, state transitions from FOS+1 exhibit the highest performance relevance in all their respective state categories i.e. the highest performance relevance of all transitions to a subsequent transient state, point and error.

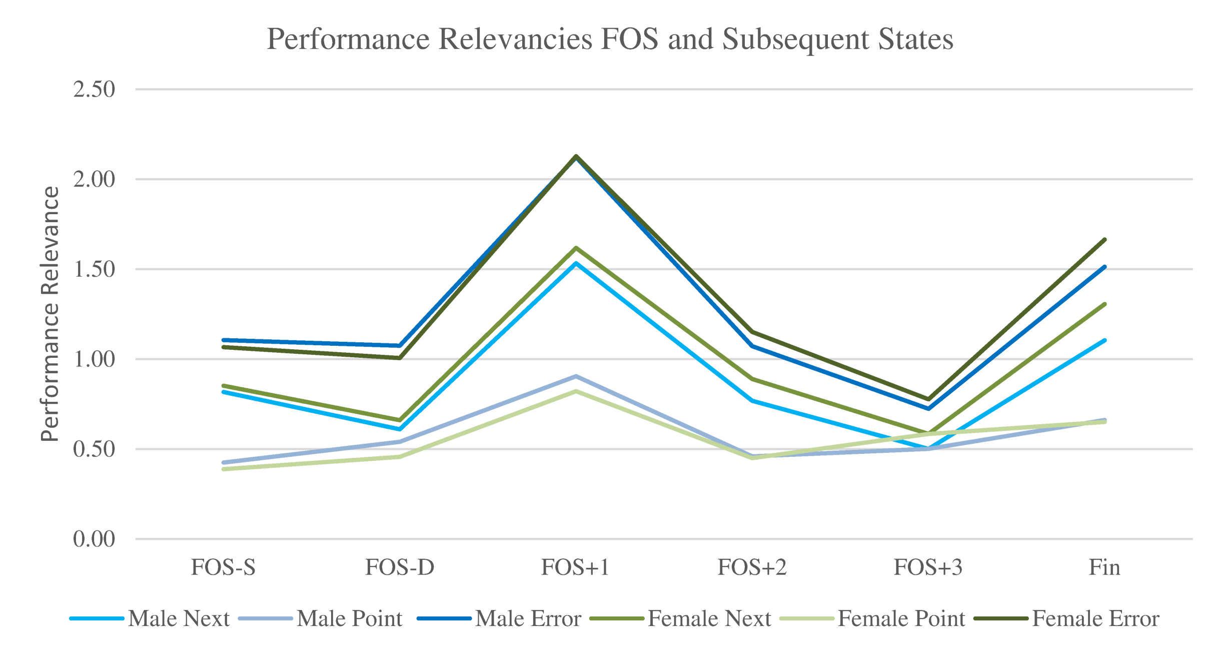

Figure 4. Performance relevancies of transitions to following shots as well as error from FOSs and subsequent shots as absolute mean values.

Discussion

The aim of this study was to introduce and validate a novel state transition model for table tennis incorporating the concept of FOS introduced by Fuchs and Lames (2021). Further it was aimed to leverage the theory of finite Markov chains to examine the relevance of state transitions representing tactical behaviors in terms of general game structure. To that end another goal was to investigate potential differences in performance relevance regarding the factor sex.

Model Validation

Assuring sufficient model validity is a crucial aspect to warrant employing the suggested method of leveraging simulations to determine the performance relevance of state transitions and corresponding tactical behaviors. First this serves as a means to assure adherence to the Markov property which is a fundamental precondition for using the theory of finite Markov chains (Lames, 2020; Pfeiffer et al., 2010). Additionally, this assures that the model predictions for point winning probability are adequate to reliably model the impact of simulated changes in transition probability.

Moreover, the present concept for a state transition model puts specific emphasis on preserving the tactical context of a rally. Previous state transition models in table tennis largely focused on technique or broader shot categories (Pfeiffer et al., 2010). While this produced very good results regarding content validity this may not always be suited to capture the full context of actions in terms of tactical behavior. For example, the tactical aim associated with playing a forehand top spin as a FOS might significantly differ from when the FOS receiver plays the subsequent shot as a top spin shot. Considering these contextual differences arguably serves the chain property of finite Markov chains which demands a certain time invariance (Lames, 2020).

Overall, the concurrency of calculated and observed values can be deemed sufficient to attest the adherence to the Markov property, thereby warranting the usage of the theory of Markov chains and associated model predictions. With a correlation of r_{cc} = .91 the calculated overall point winning probability further exhibits sufficient concurrency to allow for reliably calculating performance relevance. Generally, concurrent validity was satisfactory in all states, with associated correlations exhibiting values greater than r_{cc} = .80.

One limitation which needs to be mentioned in this regard is the slightly lower concurrent validity when compared to earlier studies using this method (Lames, 1991; Pfeiffer et al., 2010). A possible explanation for that can be found in the variability of FOS utilization when looking at the range of transition probability for the transitions Serve-FOS-S as well as Serve-FOS-D. In some cases, while there is consistent usage of the FOS, FOS usage is comparatively low. This possibly leads to discrepancies between the calculated and observed winning probabilities as the state transition model is less suited to accurately depict playing styles with a lower FOS utilization as the model is centered around the FOS and subsequent FOS+ shots. Furthermore, the current model does not differentiate between different FOS techniques which differ in terms of point winning probability (Fuchs & Lames, 2021).

Performance relevance

Calculating the performance relevance of state transitions may serve as a means to establish a connection between tactical behavior and sports outcomes. However, since the results presented in the scope of this study are based on the mean values of performance relevance, subsequent assertions refer to general game structure.

In that regard, specifically error rates can be found among the state transitions exhibiting particularly high performance relevance especially in both FOS states as well as the two subsequent states FOS+1 and FOS+2 as shown in Figure 4. This not only signifies the general importance of the FOS and subsequent shots but arguably also the general requirement to take high risk when playing FOSs as well as the high proficiency in countering and defending the FOS among players at the highest level of table tennis (Fuchs & Lames, 2021). Furthermore, when looking at previous results (Fuchs & Lames, 2021) and the underlying transition probabilities it becomes apparent that a majority of rallies ends through errors in this phase of the rally. Therefore, changing the error rates in these states naturally causes a considerable shift in winning probability as the FOS player typically holds the greatest advantage during these shots but needs to take high risk on his shots to profit from this advantage.

This is specifically apparent regarding the transition FOS+1 - Error, which not only exhibits the highest absolute performance relevance out of all state transitions but also represents the highest error rate in its corresponding transition probability. As established by Fuchs and Lames (2021) it is crucial for the FOS player to end the rally as quickly as possible following a FOS. Further, almost 50% of all rallies involving a FOS already end with this state (Fuchs & Lames, 2021). Being able to reduce the error rate in this state is thus crucial for the FOS receiver to reach later stages of the rally where his disadvantage is considerably reduced. Merely the transition Fin-Error seems odd in this context. However, considering that FOS players typically take high risk to close the rally immediately with or after the FOS, this is representative of giving away their advantageous position in the rally. Vice versa, for the FOS receiver this represents a “big point” turning around their initial disadvantage during the rally.

Regarding transitions between transient states, particularly the transitions FOS+1-FOS+2 as well as the transition Fin-Fin stand out with comparatively high degrees of performance relevance. This is somewhat in line with the assertions in the forgoing paragraph. As already mentioned, the state FOS+1 is the most disadvantageous for the FOS receiver. Similar to the relevance of the transition to error in this state, keeping the rally going is crucial for the FOS receiver at this stage in order to reduce the advantage of the FOS player. Furthermore, the FOS may thus be able to adapt to the change in play, making it easier to anticipate the subsequent shot. Similar to the transition Fin-Error, the comparatively high performance relevance of the transition Fin-Fin is again representative of the fact that the FOS player loses his advantage in longer rallies. Specifically, the first shot in this state represents the shot where a considerable decrease in winning probability for the FOS player can be observed (Fuchs & Lames, 2021). Moreover, Fin A and Fin B form a transient set where the process may stay for several strokes as opposed to all FOS states which are transient states with a maximum of one occurrence per rally. Thus, an improvement in the transitions of a transient set has several chances to become effective.

Besides, it is also interesting to look at the discrepancy in performance relevance between the transitions FOS-D-FOS+1 and FOS-S-FOS+1. This might point to a different tactical intent when attacking the serve with a FOS compared to playing the FOS after a defensive shot. In the transition FOS-S-FOS+1, the receiver arguably tries to create an early perturbation in the rally preventing the server from taking the initiative. Here the aim is likely not to immediately close the point but preventing the server to attack with a FOS of its own, which is connected to a high success rate of the server, contributing to a higher significance of the subsequent shot (Fuchs & Lames, 2021). Attacking the serve immediately with flip technique was found to be a common strategy especially in male receivers (Fuchs & Lames, 2021; Yu & Gao, 2022) but to a lesser degree also in female players (Fuchs & Lames, 2021). While female players more often immediately attack the serve with a top spin shot due to differences in serve and receiving game, this seems to be less of a problem for female players as it is easier for them to control an opponent's to spin shot (Zhang & Zhou, 2017). Moreover, immediately attacking the serve is connected to a lower immediate point rate and higher error rate which further contributes to the higher significance of the transition to the subsequent shot FOS+1 following a FOS-S when compared to a FOS-D.

Comparison between male and female players

Concerning the comparison of male and female players in terms of performance relevance it is apparent that the game structure is rather similar in both groups. However, there are still some general differences worth mentioning. These mainly concern the early and end phase of the rally namely the states Serve, Def and Fin.

First the serve and receiving game seems to be of slightly higher significance in male than in female players. This is evident through the significantly higher performance relevance of the transition Serve-Def and as well as the higher performance relevance of the transition Serve-FOS-S. A possible explanation in that regard can be found in the utilization of different FOS techniques namely a higher utilization of top spin FOS in female players in contrast to male players' higher reliance on the flip technique (Fuchs & Lames, 2021). Fuchs and Lames (2021) attributed this observation to the fact that male players prefer to serve and return short to avoid a direct top spin shot of the receiver which is supported by the findings of Djokić et al. (2020). Furthermore, this results in male receivers playing a FOS following a serve more often over the table which implies the utilization of the flip technique for that purpose (Fuchs & Lames, 2021). Alternatively, this might cause the receiver to play the return as a defensive shot allowing the server to attack with a FOS on their follow up shot. Otherwise, in cases where the receiver can play a top-spin FOS, this is more detrimental for male servers than for female servers.

The difference in service and receiving game is arguably also evident when looking at transitions from the state Def. Here the transition Def-Def exhibited a significantly higher degree of performance relevance in male players. This is also in line with previous findings. Female players seemingly prefer to play their return with a half-long or long push to take the initiative in the rally immediately while male players more often tend to return short (Zhang & Zhou, 2017). Zhang and Zhou (2017) attribute this difference to the higher difficulty for men to control a top spin shot of the serving player following their return. As already mentioned, this seems to be less of a concern for female players. As attacking a short ball with a flip technique FOS seems to be less efficient (Fuchs & Lames, 2021) it can be of greater relevance for men to induce a subsequent defensive shot by their opponent which can be attacked with a top spin FOS. In contrast the transition Def-FOS-D shows higher performance relevance in female players. This is likely representative of the fact that women are able to better defend from an opponent's top spin FOS than their male counterparts. In some cases, it could therefore be beneficial for female players to speculate on a low-quality FOS by their opponent which might give them the opportunity for a successful counterattack.

Another distinctive feature concerning sex differences in terms of performance relevance can be found in the higher relevance of the state Fin in female players, specifically in the significantly higher performance relevance of the transition Fin-Fin. Looking at the findings of Fuchs and Lames (2021) it is evident that the decrease in winning probability is bigger in women when rallies aren't closed with the shot corresponding to the state FOS+2 in the present state transition model. Consequently, it seems reasonable to assume that longer rallies are more detrimental for female FOS players, thereby explaining the aforementioned difference in performance relevance. This is also in line with the higher performance relevance in the transition FOS+3-Fin although the difference is not statistically significant for this transition. Nevertheless, game structures in male and female players are largely similar in terms of performance relevance. This is especially true for the significance of both FOS sates and the FOS+ states as evidenced by Figure 4

Conclusion

This study implemented a novel state transition model for table tennis which was focused on the concept of FOS. Furthermore, finite Markov chain modelling and methods of simulative assessment were employed to attain the performance relevance of individual state transitions within the model, representing tactical behaviors. Thereby this work provides a comprehensive analysis of the general game structure in table tennis as well as the impact of individual tactical behaviors within it. Specifically, the presented method provides novel insights in the characteristics of the FOS and especially regarding the immediately following shots. Furthermore, differences in game structure and the impact of tactical behavior were examined in terms of players' sex. This could provide a framework for future research approaching models in theoretical performance analysis with a greater focus on specific tactical behavior allowing for more concrete insights for analysts and practitioners alike.

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