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Indistinguishability of Racket and Body Kinematics during Different Table Tennis Serves for International Elite and Intermediate Players

Indistinguibilidad de la cinemática de la raqueta y del cuerpo en diferentes servicios de tenis de mesa en jugadores internaciones de élite e intermedios

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Abstract

Table tennis serves are strokes in which disguise and deception skills are important. This study aimed to investigate whether international elite table tennis players can make their racket and body kinematics more indistinguishable than intermediate players during three different serve types. Five former international elite and 8 intermediate players performed 3–12 trials of each serve type. The kinematics of the server's body and the racket was determined using a motion capture system. The time instant of racket-ball impact was determined using a high-speed video camera with the motion capture system. Misclassification rates when the serve type was classified using the racket and body kinematics were determined using linear discriminant analysis. Elite players showed higher misclassification rates for the racket kinematics than intermediate players during the early swing and follow-through phases. The body kinematics suggested that the elite players made their racket kinematics more indistinguishable using different approaches between the early swing and follow-through phases. The elite players tended to make the racket's angular velocity more similar and make the wrist rotational variables more indistinguishable in different serves compared to the intermediate players during the early swing phase. In contrast, the elite players made the racket's linear motion more variable within individual serve types than the intermediate players during the follow-through. The results suggest that intermediate players are recommended to practice making wrist angular motions more similar during the early swing phase and making racket linear motions more variable during the follow-through in order to improve the disguise skill in table tennis serves.

Keywords: *linear discriminant analysis, disguising motion, machine learning, table tennis, serve.*

Resumen

Los servicios en el tenis de mesa son movimientos en los que las habilidades para enmascarar y engañar son importantes. El objetivo de este estudio fue investigar si los jugadores de tenis de mesa de élite internacionales pueden hacer que la cinemática de su raqueta y cuerpo sea más indistinguible que los jugadores intermedios durante tres tipos de servicio diferentes. Cinco exjugadores internacionales de élite y 8 jugadores intermedios realizaron de 3 a 12 intentos de cada tipo de servicio. La cinemática del cuerpo y de la raqueta del servidor fue determinada a través de un sistema de captura del movimiento. El momento del impacto raqueta-pelota fue determinado usando una videocámara de alta velocidad con sistema de captura de movimiento. Las tasas de

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clasificación errónea cuando el tipo de servicio fue clasificado usando la cinemática de la raqueta y del cuerpo fueron determinadas por medio de un análisis discriminante linear. Los jugadores de élite mostraron tasas de clasificación errónea más altas en la cinemática de la raqueta que los jugadores intermedios durante la fase inicial del swing y la fase de terminación. La cinemática del cuerpo sugirió que los jugadores de élite hicieron su cinemática de la raqueta más indistinguible al usar diferentes enfoques entre la fase inicial del swing y la de terminación. Los jugadores de élite tuvieron una tendencia a hacer que la velocidad angular de la raqueta fuera más similar y las variables de rotación de la muñeca fueran más indistinguibles en diferentes servicios comparados con los jugadores intermedios durante la fase inicial del *swing*. En contraste, los jugadores de élite hicieron que el movimiento lineal de la raqueta fuera más variable en tipos de servicio individual que los jugadores intermedios durante la terminación. Los resultados sugieren que los jugadores intermedios deberían hacer movimientos angulares de muñeca más similares durante la fase inicial del swing y hacer que los movimientos lineares de la raqueta sean más variables durante la terminación para mejorar la habilidad para enmascarar los servicios de tenis de mesa.

Palabras clave: *análisis discriminante linear, movimiento para enmascarar, aprendizaje automático, tenis de mesa, servicio.*

INTRODUCTION

In table tennis, servers have the advantage over receivers in scoring points (Tamaki & Yoshida, 2020; Tamaki, Yoshida, & Yamada, 2017; Yoshida, Yamada, Tamaki, Naito, & Kaga, 2014; Zhang, Liu, Hu, & Liu, 2013). A recent study (Djokic, Malagoli Lanzoni, Katsikadelis, & Straub, 2020) has reported a significant association between the serve outcome and match outcome in elite player's matches, demonstrating the importance of the serve for winning a match. The importance of disguise and deception skills in the serve are highlighted in table tennis textbooks. Specifically, serve effectiveness is dependent on the opponent's difficulty judging the shot's spin and placement (Geske & Mueller, 2010), and players are recommended to learn to deceptively vary the spin, speed, and placement (Seemiller & Holowchak, 1997). Theoretically, deception and disguise in action have the intent either to mislead the opponent's anticipation or to keep the opponent in suspense about the real intention (Helm, Munzert, & Troje, 2017). In table tennis games, a player can widely vary the spin, pace, and placement of the serves. Thus, keeping the opponent in suspense about the server's real intention as long as possible would be an approach to performing effective serves. Evaluating such a skill in the serve and revealing possible differences between advanced and intermediate players would add insight into improving the skills. Previous studies on table tennis serves quantified the ball spin rates in international elite players (Lee & Xie, 2004; Yoshida, Yamada, Tamaki, Naito, & Kaga, 2014), revealed that a top player can perform two different serves with similar upper limb joint linear velocities (Wang, Zhou, Li, & Li, 2008) and demonstrated the squat serve needs higher lower limb drive than the standing serve in short serves (Yu, Shao, Baker, & Gu, 2018). However, to our knowledge, the racket and body kinematics have not yet been investigated in detail in terms of the skill of disguising table tennis serves.

Linear discriminant analysis was recently used to classify kinematic patterns into different characteristic groups (Benson et al., 2018; Fox, Ferber, Saunders, Osis, & Bonacci, 2018), to reveal what body parts provide a clue for discriminating the throw direction (Maselli et al., 2017), and to identify the kinematic variables that provide a clue for discriminating between disguised and non-disguised throws in handball (Helm et al., 2017). The present study attempted to assess the indistinguishability of the serve types by the racket and body movements in different table tennis serves using linear discriminant analysis. The racket movement is produced by the kinematic chain of the trunk and upper limb joints. By doing so, we can infer what parts of the body movements are associated with the indistinguishability by the racket movement.

A player may make the racket kinematics indistinguishable by keeping the different serve types the same as possible as he/she can or increasing the variability of the racket kinematics within individual serve types. By taking the latter approach, one may be able to remove the features of each serve type that can be used to distinguish the serve type. Determining the similarities of the racket kinematics between different serve types and their variability within individual serve types would give us insight into how players make the racket kinematics indistinguishable.

Using linear discriminant analysis, this study aimed to investigate whether elite table tennis players can make their racket and body kinematics more indistinguishable than intermediate players in three different types of serves. The present study hypothesized that elite players can make their racket and body kinematics more indistinguishable than intermediate players.

METHODS

Participants

Five former international elite (2 male, 3 female) and 8 collegiate (4 male, 4 female) table tennis players participated in the study. The mean (range) age, height, and body mass were 37.0 (30.9–54.7) years, 1.61 (1.55–1.68) m, and 56.7 (48.4–65.1) kg, respectively, for the elite players and 20.9 (19.2–21.6) years, 1.62 (1.51–1.73) m, and 57.7 (50.7 –64.7) kg, respectively, for the collegiate players. Two elite players were medalists at the Olympic Games and all elite players were medalists at the International Table Tennis Federation World Championships competitions. The elite players were retired players with high-level serve skills. Three elite players had been within three years from retirement, one elite player had retired six years ago and the remaining one player was an active elite table tennis coach. Please note that active elite players are not willing to have their serving techniques scrutinized even though the data are anonymized. All collegiate players were Kanto (a region including Tokyo) Collegiate Table Tennis League Division II or III players and categorized as intermediate players. One elite player used a Chinese penholder grip racket, while all other elite and collegiate players used shake-hands grip rackets. All participants had no recent injuries that could affect the serve performance. All participants provided written informed consent before participating in the study. The study procedure was approved by a local ethics committee.

Protocol

The participants wore tight-fitting pants and shirts and their own table tennis shoes. A total of 52 retro-reflective markers were attached to the body surface of each participant. Four markers were also attached to the lateral aspects of each participant's racket; every participant used his or her racket. After the individual warm-up, each participant was asked to perform three types of serves to a right-handed receiver, who was an experienced table tennis coach (the fourth author). The order of serve types was randomized. The last author instructed the participants regarding the next serve type before each trial by showing them a sheet on which the order was written. The receiver was not informed about the next serve type. Each participant determined three types of serve he or she considered the best set in terms of disguise in advance. The participants were asked to vary spin, pace, and/or location of the three serve types. The techniques, spins, and aimed locations of the ball's second bounce on the table as well as the number of trials for each participant are listed in Table 1. The number of trials was varied among the participants based on the time allowed for each player to participate in the experiment as well as the total time allowed for the experiment. Three-star plastic balls with 40mm diameter (Nippon Takkyu, Tokyo, Japan) were used in all trials.

Data collection

The three-dimensional coordinates of the reflective markers during serves were collected using a 16-camera motion capture system (MAC3D System; Motion Analysis, Santa Rosa, CA, USA) at 200 Hz. Images of the racket around the ball-racket impact were recorded using three high-speed video cameras (1×Phantom VEO 710, 2×Phantom MiroLC; Vision Research, Wayne, NJ, USA) at 2,000 Hz. Trigger signals for the high-speed video cameras were also recorded using the motion capture system for synchronization.

Data Analysis

Racket kinematics

The three-dimensional coordinates of the racket markers were smoothed with a zero-lag 2nd-order Butterworth low-pass filter. The filter cut-off frequencies were determined with the residual analysis. Considering the small trial-to-trial variation of the server's standing position, the position of the racket tip was determined as the position relative to the midpoint of the left and right anterior superior iliac spines at the time when the racket's resultant velocity exceeded 0.2 m/s and used for later analysis. The velocity of the racket's tip was determined using the central finite difference method. The orientation of the racket relative to the laboratory coordinate system was determined using unit quaternions, which do not suffer from singularities as Euler angle parametrization does. A unit quaternion that represents rotation through an angle θ around the axis represented by the unit vector $\boldsymbol{n}$ can be written as:

$$\hat{q} = [q_0, \boldsymbol{q}] = [q_0, q_1, q_2, q_3] = [\cos\frac{\theta}{2}, \sin\frac{\theta}{2}\boldsymbol{n}]$$

Only the imaginary part of the unit quaternion [q_1, q_2, q_3] was used in the calculation of misclassification rates because only three components of a unit quaternion are independent and were deemed significant for discrimination. The X-axis of the laboratory coordinate system was directed rightward from a server's view (Figure 1). The Y-axis was directed forward from the same view. The Z-axis was perpendicular to the X- and Y-axes pointing upward. The racket's coordinate system was determined as shown in Figure 1, while its angular velocity was determined from its rotation matrix.

Kinematic dissimilarity of racket kinematics among different serve types and its variability within individual serve types

We assessed the dissimilarity of the racket kinematics among different serve types and its variability within individual serve types during each swing phase. Then, we determined the Euclidean distances of the mean position vectors among the three serve type pairs and averaged them as follows:

$$\textit{Averaged distance} = \frac{||\overline{\mathbf{X}^{s1}}(t_k) - \overline{\mathbf{X}^{s2}}(t_k)|| + ||\overline{\mathbf{X}^{s1}}(t_k) - \overline{\mathbf{X}^{s3}}(t_k)|| + ||\overline{\mathbf{X}^{s2}}(t_k) - \overline{\mathbf{X}^{s3}}(t_k)||}{3},$$

where $\overline{\mathbf{X}^{s1}}(t_k), \overline{\mathbf{X}^{s2}}(t_k), \overline{\mathbf{X}^{s3}}(t_k)$ are the mean racket position vectors at a time t_k for each serve type (s1, s2, and s3). The averaged Euclidean distance was further averaged for each swing phase, which represents the dissimilarity of the racket position among the different serve types for each phase. We determined the position deviation vector of each trial from the mean vector. Then, the root-mean-square norm of the deviation vectors for each serve type was averaged for three serve types as follows;

$$RMS_d(t_k) = \frac{\Sigma_j \sqrt{\left[\frac{\Sigma_{i=1}^{N_j} ||\mathbf{X}_i^j(t_k) - \overline{\mathbf{X}^j}(t_k)||^2}{N_j}\right]}}{3}, (j = s1, s2, s3)$$

where $X_i(t_k), \overline{X^j}(t_k), N_j$ are the position vector of the racket tip at the time t_k, the mean position vector at t_k and the number of the trial for serve type *j*, respectively. The root-mean-square values were further averaged for each swing phase, which represents the variability of the position vector for each phase. The averaged Euclidean distances and the root mean squares of the norm of the deviation vectors for the racket linear velocity, quaternion, and angular velocity were similarly determined.

Upper trunk and racket arm kinematics

The right-handed coordinate systems for the upper trunk, upper arm, forearm, and hand segments were defined in the same way as in the study of Iino (2017). The upper trunk angles with respect to the laboratory coordinate system were determined using Euler angles (Grood & Suntay, 1983) with the rotational sequence of longitudinal rotation, lateral flexion, and anteroposterior bending. The shoulder, elbow, and wrist joints angles were also determined using Euler angles with the sequence of rotations about the mediolateral axis, anteroposterior axis, and superior-inferior axis.

The angular velocities of the body segments were determined from the rotation matrices of the respective segments. The shoulder, elbow, and wrist joint angular velocities were calculated by subtraction of the angular velocity of the proximal segment from that of the distal segment. The joint angular velocity vectors were decomposed into anatomically interpretable components aligned with the joint coordinate systems, which were defined in the same manner as in the study of Iino and Kojima (2009).

Swing phases

Time with respect to the time of ball impact (0 sec) was determined for kinematic data using 2,000Hz video images with a precision of half a millisecond. The swing duration of a table tennis serve was defined as the time from when the racket's resultant velocity exceeded 0.2 m/s to the time of ball impact. One elite player (E3) varied the initial swing motion within each serve type, and the swing duration varied widely within each serve type if it was defined as stated above. Thus, for this player, the swing duration was from the time of the peak resultant racket velocity during the initial swing motion to the ball impact. Time was first normalized to the swing duration of each serve for each participant. We then rescaled the normalized time to the unit of seconds by multiplying the mean duration of the three serves for each participant. These rescaled data were sampled at 200 Hz using cubic spline interpolation such that the data would include 0-sec data. The swing motions were then divided into three phases: early swing, -0.7 s to -0.15 s; pre-impact, -0.15 s to 0 s; and follow-through, 0 s to 0.2 s. We defined the early swing phase by not using the time when the racket's resultant velocity exceeded 0.2 m/s because we thought we needed to standardize the phase durations when comparing the linear discriminant analysis results among the different players; it is relatively easy to make different serves indistinguishable before accelerating the racket just before impact, and the serves with longer durations probably have a higher degree of similarity among the different serves. The time -0.7 sec was selected because all players began the serve motion before this time, while the time -0.15 sec was selected because all players increased the racket speed substantially after this time.

Consideration of hiding the racket behind the body or table

Several players hid their rackets from the receiver behind their body or the table. Although a receiver can estimate the server's racket motion even when he or she cannot see it, its reliability is severely degraded. Thus, we excluded the data over the duration when the receiver was thought not to be able to see the racket completely in the calculation of the misclassification rate, which will be explained in the next section. To estimate that duration, we created movies of each server's motions from the receiver's viewpoint using the marker coordinates and Matlab 3D graphics functions. In creating the movies, we assumed the receiver's viewpoints by referring to video footage because we did not determine the exact positions of the receiver. Furthermore, we considered this viewpoint as fixed throughout the swing phase. The movies did not accurately express the outline of the body segments as they were depicted as simplified geometric objects. We confirmed that ±5 cm lateral shifts of the assumed receiver's viewpoint affected the estimation of the duration by ±5 ms at most by creating multiple movies with the viewpoint shifted laterally by ±5 cm and ±10 cm. Furthermore, we treated the data equally for both groups of players. Thus, despite the limitations, we believe that the inaccuracy estimating the duration did not substantially affect the intergroup comparison.

Table 1.
Technique, spin, placement and number of trials for three types of services performed by each player.

Player	Technique			Serve 1			Serve 2			Serve 3		
	Racket side	Motion	Height of ball toss	Spin	Placement	# of trials	Spin	Placement	# of trials	Spin	Placement	# of trials
Elite												
E1	FH	standing	middle	back+side	LB	11	side	SF	11	back+side	SF	11
E2	FH	standing	middle	top+side	LB	10	top	LF	10	back	SF	12
E3	BH	squat	middle	top	LB	10	top	LF	10	back+side	SM	10
E4	FH	standing	middle	back+side	LB	11	side	SF	10	back+side	SF	10
E5	BH	standing	middle	top+side	LB	7	back+side	SF	7	top	SF	7
Intermediate												
I1	FH	standing	low	back+side	SF	5	minimal	SF	5	top	LB	6
I2	BH	standing	middle	back+side	LB	4	back+side	SF	5	side	SF	3
I3	FH	standing	middle	top+side	LB	4	back+side	SF	5	top+side	SF	4
I4	FH	standing	low	back+side	SB	5	top+side	LF	5	top+side	SB	5
I5	FH	standing	middle	side	SF	5	minimal	LB	5	top	LF	5
I6	FH	standing	low	back	SM	5	minimal	SM	5	minimal	LB	5
I7	FH	standing	middle	side	SF	5	side	SF	5	minimal	LB	5
I8	FH	standing	middle	back+side	LB	5	back+side	SF	5	top+side	LB	5

FH, forehand serve; BH, backhand serve. Placement is the aimed indication of the ball´s second bounce on the table: SB, short backhand side; SM, short middle; SF, short forehand side; LB long backhand side; LF, long forehand side for a right-handed player.

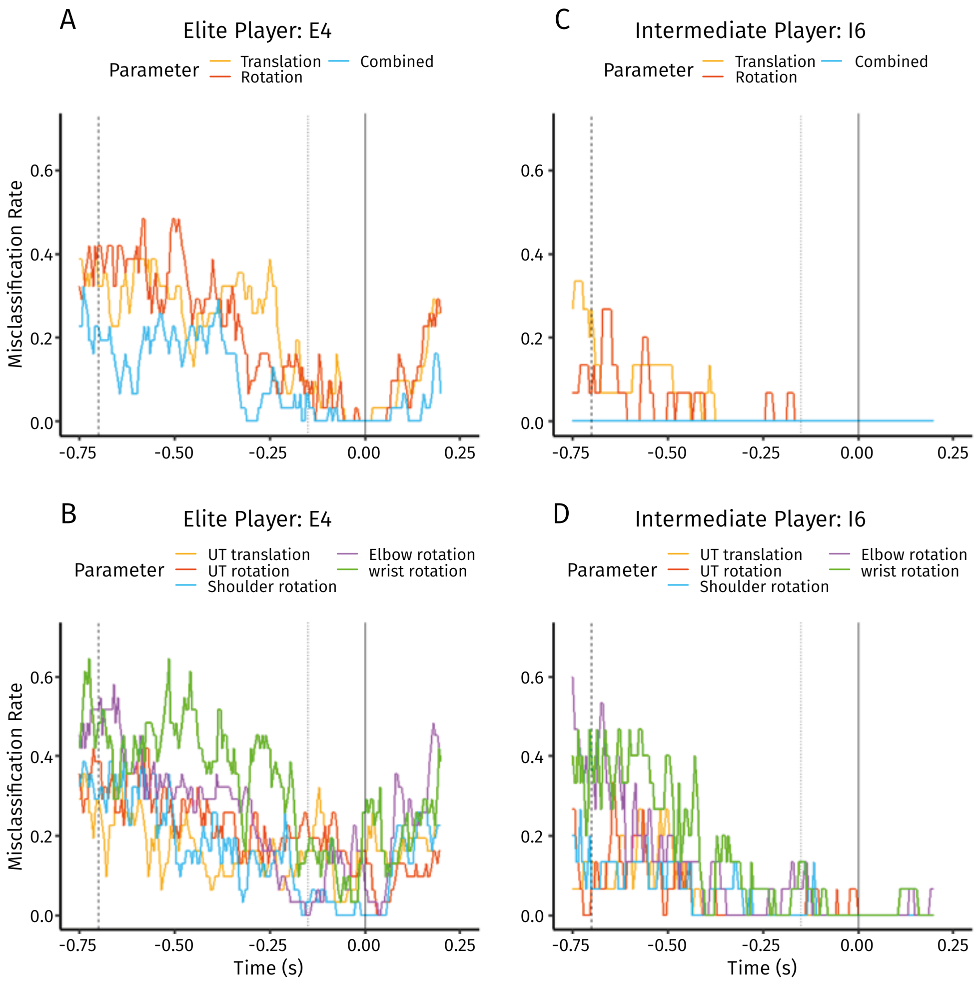

Figure 1.
Misclassification rates determined by the linear discriminant analysis with the racket kinematics and upper trunk and racket arm movements for elite player E4 (A and B, respectively) and intermediate player I6 (C and D, respectively). UT, upper trunk. The vertical lines indicate the beginnings of the early swing.

Linear discriminant analysis

We conducted the linear discriminant analysis using different sets of racket and body kinematics at each time instant. The translational variable of the racket kinematics was the 6 position-velocity coordinates of the racket tip and the rotational variable was the 6 quaternion-angular velocity coordinates of the racket. Thus, the combined variable at each time instant was a 12-dimensional vector. The translational variable of the upper trunk was the 6 position-velocity coordinates of the proximal end of the upper trunk. The rotational variable of the upper trunk was the 6 angle-angular velocity coordinates of the segment. The rotational variables of the shoulder, elbow, and wrist joints were the 6, 4, and 4 angle-angular velocity coordinates of the corresponding joints because we assumed the elbow varus/valgus and wrist longitudinal rotations do not occur. Misclassification rates were determined using a leave-one-out cross-validation procedure. In this procedure, a single data set was classified based on the remaining N-1 training data sets. This process was repeated for all N data sets. Due to the limited number of trials, the resolution of the instantaneous misclassification rate was limited; for an intermediate player with 15 total trials, the resolution was one-fifteenth (about 0.066) and a change by ±0.033 in misclassification rate could not be detected. Thus, we could not assess the misclassification rates at each time instant with high confidence; instead, we determined the mean misclassification rates over each swing phase for each set of kinematic variables by totaling the misclassification rates during each phase and dividing the answer by the number of data points during that phase.

The indistinguishability of the serve types was assessed using the misclassification rates determined by the linear discriminant analysis in the present study. This approach enabled us to assess the indistinguishability due to each of racket and body variables separately. On the other hand, the indistinguishability of the serve types to the receiver's eyes is important in a table tennis match. Separate research is required to reveal how the indistinguishability assessed by linear discriminant analysis is related to the indistinguishability to the player's eyes, which would vary among different performance levels.

Statistical analysis

Shapiro-Wilk test was used to test the normality of the misclassification rates, the mean Euclidean distances of the four racket variables, and the root-mean-square norms of the deviation vectors of the four variables. If the normality was rejected for the data set of either player group, the Wilcoxon rank-sum test was used to compare the data set between the elite and intermediate players; otherwise, a two-tailed t-test was used. In consideration of multiple testing issues, the significance level should be adjusted to reduce type I errors. It is also important to balance type I and type II errors. Thus, the level of statistical significance was set at 0.01. Linear discriminant analysis and all statistical tests were performed using R (R Core Team, 2018).

RESULTS

Results of Shapiro-Wilk normality test indicated that the following data were not normally distributed: the misclassification rates for racket translational and rotational variables during the pre-impact phase for the Intermediate players ($W = 0.689$, $p < .01$ and $W = 0.711$, $p < .01$) and for racket combined variable during all three phases for the Intermediate players (early swing: $W = 0.640$, $p < .001$; pre-impact: $W = 0.418$, $p < .001$; follow-through: $W = 0.465$, $p < .001$), the misclassification rates for shoulder rotation during the pre-impact phase for the Intermediate players ($W = 0.660$, $p < .001$) and for upper trunk translation ($W = 0.680$, $p < .01$), elbow and wrist rotations during the follow-through phase for the Intermediate players ($W = 0.732$, $p < .01$ and $W = 0.740$, $p < .01$), the root-mean-square norms of the deviation vector for the racket quaternion (orientation) within the individual serve types during the early swing phase for the Elite players ($W = 0.636$, $p < .01$), for the racket quaternion during the pre-impact and follow-through phases for the Intermediate players ($W = 0.684$, $p < .01$ and $W = 0.620$, $p < .001$), and for racket angular velocity during the pre-impact phase for the Intermediate players ($W = 0.750$, $p < .01$). Thus, Wilcoxon rank-sum test was used to compare these data set between the two groups of players.

The mean Euclidean distances of the four racket parameters upon ball impact among the three pairs of serve types did not differ significantly between both groups (Position: Elite = 0.138 ± 0.034 m, Intermediate = 0.135 ± 0.027 m, $p = .427$, Cohen's d = 0.11; Velocity: Elite = 3.93 ± 0.82 m/s, Intermediate = 2.84 ± 0.90 m/s, $p = .026$, Cohen's d = 1.25; Quaternion (Orientation): Elite = 0.423 ± 0.178, Intermediate = 0.394 ± 0.239, $p = .404$, Cohen's d = 0.13; Angular Velocity: Elite = 10.7 ± 4.2 rad/s, Intermediate = 12.3 ± 2.1 rad/s, $p = .240$, Cohen's d = 0.51).

The root-mean-square norm of the deviation vector for the racket position within the individual serve types was significantly larger for the elite players than the intermediate players during the follow-through phase (Table 2). The Euclidean distances between the mean racket kinematic variables averaged for three pairs of the three different serves were not significantly different for all variables and all swing phases between the elite and intermediate players (Table 2).

Two elite and two intermediate players hid their rackets behind their bodies or the table. Data over the duration when a player hid the racket in all trials

(100%) for all serve types, which typically ranged from 0.1 sec to 0.2 sec, were excluded in the calculation of the misclassification error.

The misclassification rates for translational and rotational racket variables and the combined variable tended to decrease toward ball impact and increase after impact for elite players (Table 3 and Figure 1) whereas the misclassification rates tended to decrease towards ball impact and remained low values after impact for intermediate players (Table 3 and Figure 1). The misclassification rates for the body kinematic variables showed similar time-varying patterns as for the racket kinematic variables (Figures 1).

The mean misclassification rates for the combined racket variable during the early swing phase of the elite players were significantly higher than those of the intermediate players (Table 3). The misclassification rates during the pre-impact phase for the racket kinematic variables did not differ significantly between the elite and intermediate players. The misclassification rate for the translational racket kinematic variable during the follow-through phase was significantly higher for the elite players than for the intermediate players (Table 3). For the body kinematic variables, the misclassification rate for the wrist rotational variable during the pre-impact phase was significantly higher for the elite players than the intermediate players and the rate tended to be significantly higher for the elite players during the early swing and follow-through phases. The misclassification rate for the elbow rotational variable also tended to be higher for the elite players than the intermediate players during the follow-through phase (Table 3).

The present study aimed to examine whether elite table tennis players can make the racket and body kinematics more indistinguishable than intermediate players during three different serves. For that purpose, linear discriminant analysis was performed on the different sets of racket and body kinematic variables. The results supported the hypothesis that elite players can make their racket and body kinematics more indistinguishable than intermediate players.

The mean Euclidean distances of all racket parameters among the three pairs of serve types at ball impact did not differ significantly between the elite and intermediate players (Table 2). The mean distances for the linear velocity tended to be larger for the elite players than the intermediate players. This indicates that the elite players varied the racket kinematics at impact for the three serves at least to a similar extent compared to the intermediate players. Therefore, it is very unlikely that the higher misclassification rates for the elite players than the intermediate players observed in the present study (Table 3) were due to the variation of the three serves being smaller for the elite players than the intermediate players.

Table 2.
Root-mean-square norm of the deviation vectors of four racket variables within individual serve types averaged for three serve types and euclidean distance between the mean racket kinematic variables averaged for three pairs of three different serves in elite and intermediate players.

	Early swing				Pre-impact				Follow-though			
	Elite	Intermediate	*p*-value	Cohen´s d	Elite	Intermediate	*p*-value	Cohen´s d	Elite	Intermediate	*p*-value	Cohen´s d
Root-mean-square norm of the deviation vectors within individual serve types averaged for three serve types												
Position (m)	0.095 ± 0.073	0.074 ± 0.044	0.578	0.35	0.093 ± 0.041	0.071 ± 0.030	0.334	0.61	**0.137 ± 0.021**	**0.096 ± 0.024**	**0.009**	**1.85**
Velocity (m/s)	0.61 ± 0.47	0.56 ± 0.29	0.839	0.13	0.91 ± 0.26	0.82 ± 0.51	0.698	0.21	1.71 ± 0.29	1.24 ± 0.39	0.032	1.36
Quaternion	0.19 ± 0.19	0.12 ± 0.06	0.833	0.47	0.20 ± 0.10	0.20 ± 0.19	0.622	-0.01	0.28 ± 0.16	0.23 ± 0.18	0.524	0.29
Angular Velocity (rad/s)	2.38 ± 1.69	1.57 ± 0.74	0.359	0.62	2.95 ± 0.63	2.95 ± 1.81	0.284	0.02	6.90 ± 2.70	5.23 ± 1.55	0.258	0.76
Euclidean distances between the mean racket kinematic variables averaged for three pairs of three different serves												
Position (m)	0.11 ± 0.10	0.074 ± 0.044	0.59	0.36	0.19 ± 0.07	0.16 ± 0.04	0.42	0.52	0.25 ± 0.17	0.19 ± 0.09	0.504	0.44
Velocity (m/s)	0.58 ± 0.33	0.56 ± 0.29	0.671	-0.26	2.14 ± 0.50	1.83 ± 0.51	0.324	0.59	2.68 ± 0.50	2.73 ± 1.14	0.908	-0.06
Quaternion	0.17 ± 0.12	0.12 ± 0.06	0.823	-0.13	0.46 ± 0.08	0.49 ± 0.22	0.704	-0.2	0.47 ± 0.19	0.48 ± 0.24	0.962	-0.03
Angular Velocity (rad/s)	1.75 ± 0.19	1.57 ± 0.74	0.138	-0.84	6.43 ± 0.71	7.74 ± 2.11	0.138	-0.84	8.63 ± 3.62	9.04 ± 3.68	0.848	-0.11

Table 3.
Misclassification rates for racket and body kinematics during three phases of three serve types of elite and intermediate players.

	Early swing			Pre-impact			Follow-thorugh		
	Elite	Intermediate	*p*-value	Elite	Collegiate	*p*-value	Elite	Intermediate	*p*-value
Racket									
Translation	0.183 ± 0.108	0.089 ± 0.070	0.132	0.016 ± 0.021	0.013 ± 0.022	0.848	**0.105 ± 0.043**	**0.022 ± 0.031**	**0.008**
Rotation	0.206 ± 0.119	0.067 ± 0.047	0.058	0.035 ± 0.050	0.014 ± 0.023	0.288	0.073 ± 0.028	0.035 ± 0.028	0.044
Combined	**0.078 ± 0.085**	**0.001 ± 0.002**	**0.002**	0.006 ± 0.010	0.001 ± 0.004	0.417	0.014 ± 0.010	0.003 ± 0.007	0.012
Body									
UT translation	0.115 ± 0.039	0.098 ± 0.051	0.503	0.042 ± 0.053	0.048 ± 0.046	0.836	0.060 ± 0.070	0.043 ± 0.037	0.645
UT rotation	0.156 ± 0.064	0.095 ± 0.043	0.103	0.064 ± 0.071	0.027 ± 0.022	0.314	0.067 ± 0.048	0.030 ± 0.044	0.062
Shoulder rotation	0.136 ± 0.055	0.098 ± 0.045	0.238	0.010 ± 0.010	0.023 ± 0.035	0.644	0.064 ± 0.047	0.033 ± 0.033	0.233
Elbow rotation	0.198 ± 0.066	0.190 ± 0.105	0.868	0.058 ± 0.029	0.044 ± 0.031	0.445	0.159 ± 0.052	0.077 ± 0.088	0.045
Wrist rotation	0.302 ± 0.066	0.173 ± 0.086	0.012	**0.116 ± 0.024**	**0.038 ± 0.042**	**0.001**	0.142 ± 0.051	0.069 ± 0.088	0.030

UT: Upper trunk; Values are shown as mean ± standard deviation. Number in bold face indicate significant differences between elite and intermediate players.

DISCUSSION AND IMPLICATIONS

The elite player made their racket kinematics more indistinguishable during the early swing and follow-through phases than the intermediate players (Table 3). The results of the misclassification rates during the pre-impact phase (Table 3) suggest that the elite players could perform three types of serves with more indistinguishable wrist motions than the intermediate players although the indistinguishability of the racket kinematics was not significantly different between both players group. Thus, the results suggest that receivers may be recommended to focus on the racket motion rather than the wrist motion during the pre-impact phase for judging the serve type.

The results also revealed that the elite players made their racket kinematics more indistinguishable using different approaches between the early swing and follow-through phases. This is explained below. In the early swing phase, the elite players made the combined racket variable more indistinguishable than did the intermediate players (Table 3). The variability of the racket variables within individual serve types in this phase was similar in the elite and intermediate players (Table 2), suggesting that making the racket kinematics more variable within individual serve types was not an approach of the elite players to making the racket variables more indistinguishable in this phase. Though the mean Euclidean distances between the racket variables for the three serve types were not significantly different between both groups, the effect size of the difference was large for the angular velocity and the distance was smaller for the elite players (Table 2). It is possible that a more similar angular velocity among the different serves contributed to a more indistinguishable racket variable for the elite players. A tendency toward a more indistinguishable wrist rotational variable for the elite players (Table 3) indicates that the wrist motion may be related to the more indistinguishable racket kinematics of the players.

During the follow-through, the racket linear position was more variable within individual serve types for the elite players than the intermediate players. This likely contributed to the more indistinguishable translational racket motion during this phase for the elite players. The elite players tended to make the elbow and wrist motions more indistinguishable than the intermediate players during the follow-through phase. Thus, a more variable racket position for the elite players may be attributed to their elbow and wrist motions. Based on the results, intermediate players are recommended to practice serves with variable follow-through motions for each serve type, which is not addressed in table tennis textbooks (Geske & Mueller, 2010; Seemiller & Holowchak, 1997) although the importance of disguising and deceptive serve motions is highlighted there.

Some limitations exist in this study. First, the elite players were retired players, and the number of elite players was low. Five elite players are not enough to make generalization about international elite players. Thus, the findings obtained in the present study should be considered with these in mind. Second, the elite group included a pen holder grip user whereas all intermediate players were shake-hands grip users. The present study could not reveal whether differences exist in racket and body kinematics distinguishability between pen holder and shake-hands grip types or between male and female players. Then, the players performed a low number of trials, which prevented us from assessing the instantaneous values of the misclassification rate. Finally, the indistinguishability of the different serves was only assessed by linear discriminant analysis. Future studies are needed to clarify how the assessment by linear discriminant analysis is related to the judgment by players' perceptions with different performance levels.

CONCLUSION

We compared the indistinguishability of racket and body kinematics during three different table tennis serves between elite and intermediate players. Specifically, the misclassification rates when the serve type was classified using the racket and body kinematics were determined using linear discriminant analysis. Elite players showed significantly higher misclassification rates for the racket kinematics than intermediate players during early swing and follow-through phases. The elite players tended to make the racket's angular velocity more similar in different serves compared to the intermediate players during the early swing phase. In contrast, the elite players made the racket's linear motion more variable within individual serve types than the intermediate players during the follow-through. In short, the results suggest that the elite players made their racket kinematics more indistinguishable using different approaches between the early swing and follow-through phases. Furthermore, the elite players showed a higher misclassification rate for the wrist motion during the pre-impact phase than the intermediate players, suggesting a higher ability of the elite players to make the wrist motion more indistinguishable immediately before impact.

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