Paper

Attempt to evaluate serve performance of Japanese top level tennis players using a doppler radar device -Focusing on the ball speed, the spin rate, and the number of trials required to achieve the task-

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This study attempted to comprehensively quantify (1) the ball speed and (2) spin rate of the serve and (3) the number of trials required to achieve the task in Japanese top-level tennis players (male and female professionals, male and female student athletes, male and female junior athletes, male and female wheelchair athletes). The purpose was to use the quantified data as a new evaluation index for serve performance. The subjects were instructed to hit the flat, slice, and kick serves into the designated area. The subjects attempted each type of serve towards the target area until five serves for each type successfully landed in that area. As a result, the approximate curve obtained from the speed and spin rate of the serve (flat, slice, kick) tended to be located in the upper right of the figure (X-axis: speed, Y-axis: spin rate) at the highest competition level. In addition, from the number of trials required to complete the task, we were able to obtain materials for inferring players' serving skills. Based on these findings, data feedback to the players would be important to promote self-understanding of their serving skills with correcting the gap between the players' subjective and objective evaluation. This study suggests an index that can contribute to improving the serve performance of not just top-level tennis players but also all recreational tennis players.

Key words : TRACKMAN, feedback, serve performance

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1. Introduction

Sakurai et al. (2013) and Adachi (1999) states that an important technique to separate wins and losses in tennis is the serve. Focusing on the serve ball speed in the 2019 Wimbledon Men's Singles Final of Novak Djokovic vs Roger Federer, both competitors achieved high speed both in the 1st and 2nd serve and in terms of maximum and average speed. The record of Djokovic was as follows: the maximum speed of the 1st serve was 199 km/h, the average speed of the 1st serve was 189 km/h, and the average speed of the 2nd serve was 158 km/h. Federer's record was: the maximum speed of the 1st serve was 202 km/h, the maximum speed of the 2nd serve was 173 km/h, the average speed of the 1st serve was 187 km/h, and the average speed of the 2nd serve was 154 km/h (Official homepage of The Championships, Wimbledon 2019). Paying attention to the quarterfinals, Roger Federer and Kei Nishikori had similar serve speeds in the tournament. Federer's serve speeds were 202 km/h (first serve maximum), 173 km/h (second serve maximum), 187 km/h (first serve average), and 154 km/h (second serve average). On the other hand, Nishikori's serve speeds were 196 km/h (first serve maximum), 175 km/h (first serve average), and 148 km/h (second serve average). Looking at this value, Federer's value was higher than Kei Nishikori's value in all serves (Official homepage of The Championships, Wimbledon 2019). Kei Nishikori is one of Japan's leading tennis players and one of the world's top players. In 2011, he was ranked 4th in the world ranking with his special jumping stroke skill called Air-Kei. However, Nishikori's serve lacks power (as seen in the above comparison between Roger Federer's serve speed) and stability compared to the players who have been ranked first in the world. Further improvements in serve performance are essential for him to win the Grand Slam.

From these facts, strengthening serves is essential for Japanese tennis players (including Kei Nishikori) to win the Grand Slam title. In major tournaments, such as the Grand Slam, ATP, and WTA TOUR, in recent years, the Challenge System plays an important role in enhancing the fairness of the competition. When players use the Challenge System, players can request the referee to make a judgment by an automatic judgment line system in a scene where it is difficult to distinguish whether the ball was in or out from the court. Also, information on shot data, such as the serve, is immediately analyzed by "The Hawk-Eye Officiating System" (manufactured by Hawk-Eye Innovations, UK: hereinafter Hawk-Eye) and "IBM SLAMTRACKER." The feedback data from these machines are provided not only to the players and coaches but also to the viewers of the match. The main analysis items provided by "Hawk-Eye" and "IBM SLAMTRACKER" are 1st and 2nd serve success probabilities, point earning rate, ball speed, and course. Players and coaches can visualize the data and use it to improve performance. Certainly, the ball speed and course of the serve are the major factors that separate the match's wins and losses, and they are indicators for evaluating the serve, but to determine the quality of the serve in more detail, there is a necessity to pay attention to the movement of the ball (spin rate in addition to speed). The tennis serve is mainly made up of three types: flat, slice, and kick. The characteristic of the flat serve is an aggressive ball type with high speed and low rotation speed. The slice is a horizontal rotation-type sphere, and it can push the receiver out of the court after bouncing. The kick is also known as a spin serve, and because it is a top-spin serve, it has the characteristic of bouncing high. In particular, the rotation of the ball causes a big change after bouncing, which may cause an error in the opponent’s or receiving technique, causing an error or misjudgment. It is common to have subjects hit three types of serves when researching a serve. Most of the previous studies have used speed guns and high-speed cameras to analyze ball speed. However, some researchers consider that the trajectory of the ball after the serve and the movement after landing in the service area are influenced by the rotation of the ball(Brody, 1987; Brody et al., 2002; Cross and Lindsey, 2005). Kreighbaum and Hunt (1978) presented five variables (i.e., initial ball velocity, direction of ball spin axis, ball spin rate, projection angle, and air density) as factors for determining the quality of the hit ball and the trajectory of the ball. To evaluate tennis players' serve performance, spin rate of the ball, other than the speed of the ball, is thought to be an important indicator. This is because the spin rate of the ball, which causes the trajectory of the ball to change, is to be a factor that induces misses in the opponent's prediction of the ball bounce and receiving skills. Sakurai et al. (2013) and Muramatsu et al. (2015) conducted studies on the ball speed and spin rate of the serve. Muramatsu et al. (2015) focused on the speed and spin rate of the world's top-level tennis players and classified the tendencies of the 1st and 2nd serves. They reported that a player with a high competition level displayed a high ball speed and high spin rate. However, the data analyzed in this study was an extraction from the propositions of an actual match. Therefore, it can be presumed that this study did not strictly control the type of serve. In other words, in actual games, because players always have tactics of what kind of serve they use depending on the opponent and the situation in the game, in addition to not necessarily hitting the first serve with a fastball ball, there is a possibility that players do not hit the second serve, which requires a high success rate with a rotating ball. Therefore, in these previous studies, it remained unclear what kinds of serves (i.e., flat, slice, or kick) players used. Indeed, these studies provided valuable data on the world’s top level players. After a thorough literature search, however, we do not know of any study examining the data on the national top level players. Based on this research background, the objective of the present study was to clarify the characteristics of serves in Japanese top level players. We recruited male and female professional players, university and junior top players, and Paralympian wheelchair players. We focused on the serve speed and spin rate as well as accuracy and stability in flat, slice, and kick as indexes of the serve performance. These data would be useful as evaluation indexes to improve the serve performance among Japanese tennis players.

2. Methods

2. 1. Subjects

The subjects in this study were: 12 men's professional tennis players, including the Olympic athletes within the top 50 in the ATP world rankings (henceforth; MPro); two women professional tennis players, including Olympic participants who are in the top 60 in the WTA world rankings (henceforth; FPro); 17 top university male players who have experience in winning the championship of the All Japan University's Championship Tournament (henceforth; MU); 11 top university female players who have experience in winning the championship of the All Japan University's Championship Tournament (henceforth; FU); nine top-level boys players (henceforth; MJr); seven top-level girls players (henceforth; FJr); one men's Paralympian wheelchair tennis player (henceforth; MP); and one female's Paralympian wheelchair tennis player (henceforth; FP). The total number of subjects was 60. Table 1 shows the physical characteristics of the target players. The competition level in each group is defined as follows.

The competition level in each group was classified according to the following criteria:

1. MPro and FPro: five Olympics contestants; five All Japan Tennis Championships singles and doubles champions; and four All Japan Tennis Championships singles and doubles final four participants (14 subjects in total).

2. MU and FU: four All Japan University Tennis Championships singles and doubles champions; four All Japan University Tennis Championships singles and doubles final four participants; six All Japan University Tennis Championships singles and doubles final eight participants; and 14 who moved on to the tournament (28 subjects in total).

3. MJr and FJr: 13 who went to the final eight or higher in the All Japan Junior and Inter-High School singles and doubles category (13 subjects in total).

4. MP and FP: two Paralympian wheelchair tennis medalists (two subjects in total).

This study was approved by the Nippon Sport Science University Ethics Review Committee (Approval No. 017-H943). The subjects were provided with written and verbal information regarding the purpose and contents of the study. It explained that the results were not to be used for anything other than the purpose of this study and that the participation of the experiment should be voluntary. In addition, it included an explanation that there should be no disadvantage for not participating. Finally, subjects could cancel their participation in the study even during the measurement.

2. 2. Experimental design

Before the experiment, the subjects had time to sufficiently hit three types of serves (flat, slice, and kick) as a warm-up. We asked the subjects to use the racket that they were accustomed to as the racket for experimental

Table 1. Physical characteristics in each group

		Age (yrs)	Height (cm)	Seat height (cm)	Weight (kg)
	n	Mean ± SD	Mean ± SD		Mean ± SD
MPro	12	29.1 ± 6.2	176.5 ± 4.2		73.7 ± 6.2
MU	17	20.3 ± 1.3	174.8 ± 5.4		66.6 ± 6.6
MJr	9	17.9 ± 0.8	172.0 ± 3.5		62.2 ± 5.4
FPro	2	22.9 ± 0.0	159.7 ± 4.9		53.4 ± 5.8
FU	11	20.0 ± 1.0	162.3 ± 5.3		59.8 ± 7.3
FJr	7	17.5 ± 0.7	163.8 ± 5.4		56.3 ± 3.7
MP	1	34.2	171.1	140.7	62.4
FP	1	24.0	141.5	125.0	46.2

MPro: Male Professional, MU: Male University, MJr: Male Junior, FPro: Female Professional, FU: Female University, FJr: Female Junior, MP: Male Paralympian, FP: Female Paralympian trials. The ball used for the experiment was DUNLOP FORT (International Tennis Federation ITF Certified Ball/ Japan Tennis Association JTF Certified Ball, Pressure Rise Tennis Ball, manufactured by DUNLOP). The serve hitting position was specified at a position that was 0.5 m to the right of the center mark. The subjects were required to hit flat and kick serves to the center direction (T zone), and the slice serve to the wide direction with their maximum effort. Each serve was considered a successful trial by landing in the target area (Fig. 1), and five balls of each successful trial (flat: 5 balls, slice: 5 balls, and kick: 5 balls, for a total of 15 balls) were considered for analysis. Regarding the ball type of the serve, the judgements were made when the following two criteria matched: report from the subject, and a judgement of two experienced tennis coaches and a professional tennis player. Only the serves that were judged as being the same ball types were analyzed.

2. 3. Experimental equipment

To measure the ball speed and the spin rate of the serve, we used TRACKMAN, a measuring device that can track and measure Doppler radar from launching to landing of the ball. The accuracy of TRACKMAN was examined in the study of Sato et al.(2017). They compared the ball speed and spin rate calculated from TRACKMAN and VICON, showing high correlation (speed, r = 0.9969; spin rate, r = 0.9788). Based on this finding, we decided to adopt TRACKMAN as a device for measuring the movement of the ball in this study. During measurement, the center of TRACKMAN was placed on the extension of the center mark, 5.26 m behind the baseline, and 2.65 m in height, so that the range of the doppler radar emitted from TRACKMAN could sufficiently cover the sideline of the court (Fig. 1).

2. 4. Statistical processing

For a comparison of the ball speed and spin rate of the three types of serves and the number of trials required to achieve the task within the group, a one-way analysis of variance (ANOVA) with no repetition was conducted. If significant main effects were found, Bonferroni's multiple comparison tests were performed. We also analyzed the correlation between the ball speed and the spin rate. This analysis was performed after checking data with a normal distribution using the Kolmogorov-Smirnov test. If a normal distribution was confirmed, Pearson's correlation was calculated. If non-parametric data were found, Spearman's correlation was analyzed. Since data with a normal distribution was found in MPro, FPro, FU, MJr, and FJr, Pearson's correlation was performed. On the other hand, since non-parametric data was found in MU, Spearman's correlation was performed. Regarding MP and FP (Paralympians), the actual values were shown

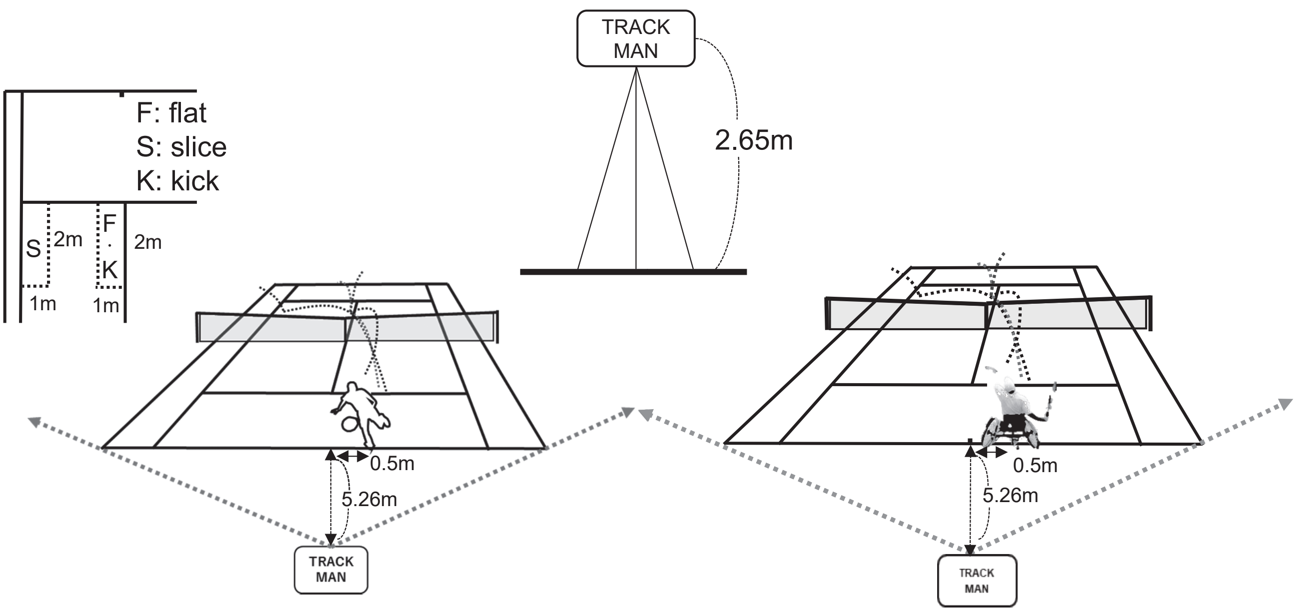

Fig 1. Experimental set-up for recording

because the number of subjects was 1, respectively.

3. Result

3. 1. Measurement results of the ball speed and spin rate

3. 1. 1. Average ball speed of the three types of serves in each group

Table 2 shows the average ball speed of the three types of serves in each group. In FPro, there was no significant difference between the flat and slice, or slice and kick, but there was a significant difference between flat and kick ($p < 0.001$). In FP, there was no significant difference between the flat and slice, but there were significant differences between the flat and kick and between the flat and slice ($p < 0.001$). In the other groups (MPro, MU, MJr, MP, FU, and FJr), there was a significant difference in the average ball speed of the three types of serves ($p < 0.001$).

3. 1. 2. Average spin rate of the three types of serves in each group

Table 3 shows the average ball spin rate of the three types of serves in each group. In FJr, there was no significant difference between the flat and slice, but there was a significant difference between the flat and kick ($p < 0.001$). In MP, there was no significant difference between the slice and kick, but there was a significant difference between the flat and slice and between the flat and kick

Table 2. Average ball speed(km/h) of 3 types of service in each group

	flat	slice	kick			
	Mean ± SD	Mean ± SD	Mean ± SD	df	F	p value
MPro	191.1 ± 6.8bc	161.1 ± 9.8ac	137.6 ± 9.8ab	2	178.26	.000
MU	187.3 ± 9.0bc	164.0 ± 9.1ac	135.7 ± 7.3ab	2	320.69	.000
MJr	176.3 ± 8.6bc	151.9 ± 7.3ac	138.3 ± 8.3ab	2	118.25	.000
FPro	159.9 ± 2.5c	145.6 ± 2.6	128.7 ± 3.5a	2	627.75	.002
FU	143.7 ± 8.5bc	128.8 ± 9.2ac	116.5 ± 12.1ab	2	47.65	.000
FJr	146.7 ± 17.5bc	127.9 ± 16.6ac	119.6 ± 10.1ab	2	10.52	.002
MP	134.6 ± 3.9bc	123.7 ± 3.9ac	116.1 ± 3.4ab	2	30.62	.000
FP	104.2 ± 4.9c	101.8 ± 3.0c	91.9 ± 4.2ab	2	12.73	.000

a: significant difference with flat ($p < 0.001$), b: significant difference with slice ($p < 0.001$), c: significant difference with kick ($p < 0.001$)

Table 3. Average spin rate(rpm) of 3 types of service in each group

	flat	slice	kick			
	Mean ± SD	Mean ± SD	Mean ± SD	df	F	p value
MPro	1232.8 ± 367.6bc	3071.1 ± 922.2ac	4371.1 ± 520.2ab	2	256.19	.000
MU	1175.9 ± 267.1bc	2889.4 ± 630.9ac	4229.5 ± 319.4ab	2	445.29	.000
MJr	1369.0 ± 460.6bc	2969.3 ± 762.4ac	3597.7 ± 600.3ab	2	97.28	.000
FPro	1341.7 ± 143.2bc	2485.2 ± 295.9ac	3331.5 ± 208.5ab	2	98.26	.010
FU	1232.1 ± 347.3bc	2467.2 ± 560.2ac	3059.7 ± 743.9ab	2	49.75	.000
FJr	1341.0 ± 405.5c	2517.2 ± 845.8	2821.2 ± 664.4a	2	13.67	.001
MP	2369.0 ± 196.8bc	3210.0 ± 353.8a	3410.9 ± 88.7a	2	26.68	.000
FP	1741.1 ± 272.9c	1774.2 ± 196.6c	2468.8 ± 157.3ab	2	18.37	.000

a: significant difference with flat ($p < 0.001$), b: significant difference with slice ($p < 0.001$), c: significant difference with kick ($p < 0.001$)

(p < 0.001). In FP, there was no significant difference between the flat and slice, but between the flat and kick, and between the slice and kick there was a significant difference (p < 0.001). In all other groups (MPro, MU, MJr, FPro, and FU), there was a significant difference in the average spin rate of the three types of serves (p < 0.001).

3. 1. 3. Relationship between ball speed and spin rate of serves in each group

Focusing on the regression equation obtained from the ball speed and spin rate of the serve in each group calculated from TRACKMAN, the following correlations were found: r = -0.94 (MPro), r = -0.95 (MU), r = -0.81 (MJr), r = -0.97 (MP), r = -0.97 (FPro), r = -0.74 (FU), r = -0.81 (FJr), and r = -0.99 (FP). Significant negative correlations were observed in all groups. Focusing on the competition level, MPro's results were located in the most upper-right position followed by MU, MJr, MP, FPro, FU, FJr, and FP, respectively (Fig. 2).

3. 1. 4. Comparison of the number of serves trials required to achieve the tasks within the each group

Figures 3-5 show a comparison of the number of serves trials required to achieve the tasks within the each group. The number of serves trials required to complete the tasks of the serve (flat, slice, kick) in each group was not significantly different among all the serves in MPro. For MU and MJr, there was a significant difference between all the serves (MU: F = 11.7, p < 0.05; MJr: F = 44.8, p < 0.05).

FPro showed no significant differences between all serves. FU and FJr showed no significant differences between the slice and kick, but there were significant differences between the flat and slice and between the flat and kick (FU: F = 25.3, p < 0.05; FJr: F = 11.4, p < 0.05).

In MP, it was flat: 8 (th), slice: 6 (th), and kick: 6 (th). In FP, it was flat: 8 (th), slice: 13 (th), and kick: 17 (th).

4. Discussion

In the present study, we investigated the characteristics of flat, slice, and kick serves in Japanese top-level tennis players. We were able to obtain the following main findings. The approximate curve (X-axis: speed, Y-axis: spin rate) was obtained from the speed and spin rate of the serve (flat, slice, kick). The higher the competition level, the more likely it was to be located in the upper-right corner of the approximation curve. In addition, we were able to obtain knowledge for evaluating serve performance from the number of trials required to achieve the task.

4.1. Average ball speed of the three types of serves in each group

Focusing on the values of the average ball speeds of

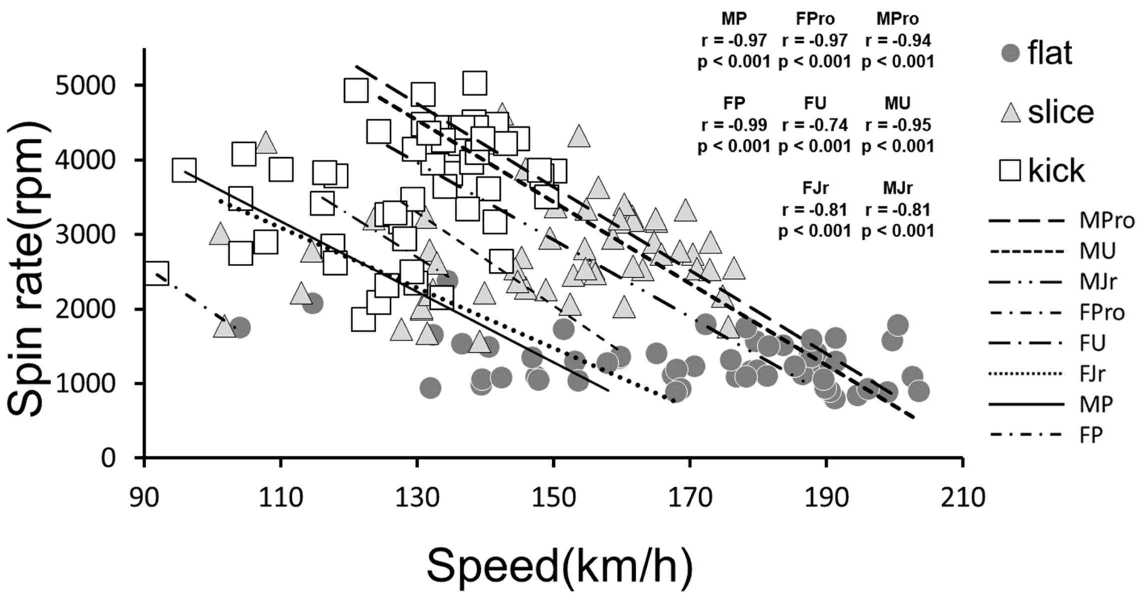

Fig 2. Relationship between ball speed and spin rate of serves in each group(MPro, MU, MJr, FPro, FU, FJr, and FP).

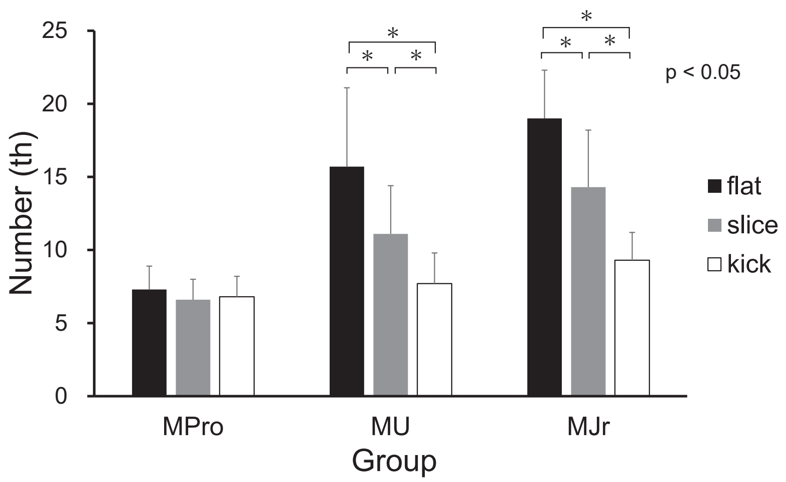

Fig 3. Comparison of the number of serves trials required to achieve the tasks within the each group. (MPro, MU and MJr).

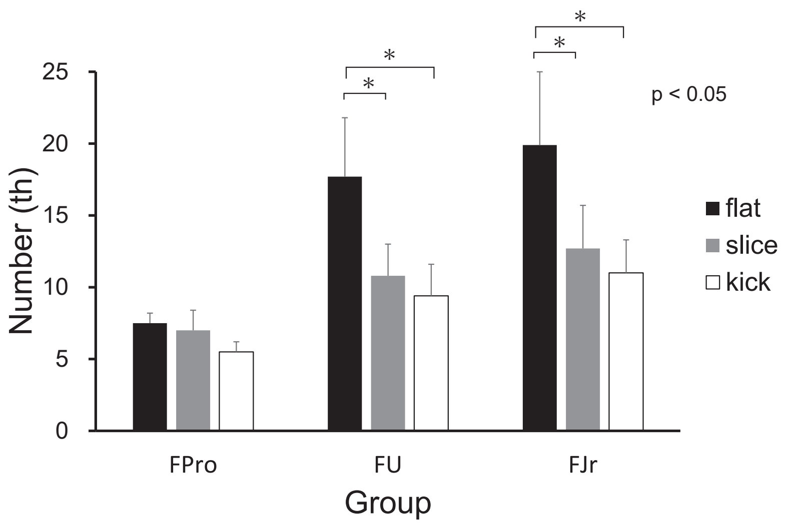

Fig 4. Comparison of the number of serves trials required to achieve the tasks within the each group. (FPro, FU and FJr).

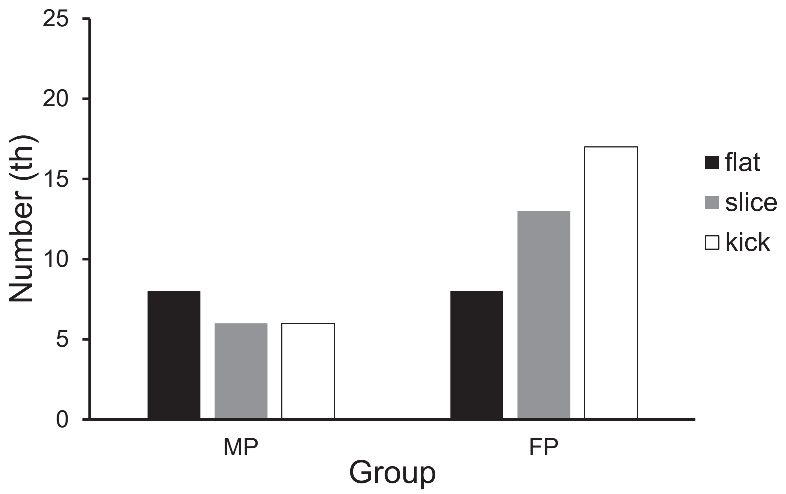

Fig 5. Number of attempts of serves trials required to accomplish the task in MP and FP(Paralympian group).

the three types in Japanese top-level tennis players' serves (MPro, MU, MJr, FPro, FU, FJr, MP, and FP) measured in this study (Table 2), in all groups except for FPro and FP, the speed of the serve was higher in the order of the flat, slice, and then kick. In this regard, we considered that the spin rate of the ball, which is caused by the difference in the type of serves, had an influence on the results. Murata et al. (2014) reported that racket swing after the serve was directed characteristically to the right in right handed players (left in left-handed players) for the slice serves, and to the vertical direction for the kick serves, compared with the flat serves. We presumed that the direction and speed of the racquet swing affected the spin rate of the ball. Moreover, since there is a tradeoff relationship between ball speed and spin rate (Sakurai et al., 2013), we assumed that the direction and the speed of the racquet swing affected the ball speed. Finally, focusing on the world top-level Japanese Paralympian wheelchair tennis players, MP showed high values of serve speed in the order of the flat, slice, and then kick. This was in the same order as Japanese top-level tennis players who are able-bodied people. In addition, the three types of serving speeds were approximately the same as the values of FU and FJr. This result may be related to the higher performance in MP recruited in the present study. In addition to the technique of hitting all the flat, slice, and kick serves, the player was able to move his upper limb, arm, and the racquet smoothly even from a sitting state on the wheelchair. Bartlett et al. (1995) stated that, in tennis, the net is set at a fixed height (0.914 m), so it is necessary to heighten the hitting position to obtain a higher ball speed after impact. In addition, with regard to the influence of lower extremity movements, Tanabe and Ito (2007) measured the serving speed in the sitting posture and the standing posture for able-bodied people. They found that in the sitting posture, the speed was 37.9 ± 2.3 (m/s), and in the standing posture, 49.3 ± 1.6 (m/s). In other words, the contribution of the lower extremity to the serving speed was estimated to be about 30%. However, for MP, even though there was absence in power delivered from the lower extremity (approximately 30%), the player was able to complement the power from the lower extremity by efficient chain movement of the upper extremity and high serving skills. Furthermore, in the case of FP, the flat and slice serves were equally high, followed by kick serves. In the kinematic comparison experiment of serves based on the success and failure of 11 elite tennis players conducted by Whiteside et al. (2015), the hitting height was about 150% of the player's height. According to the opinion of Whiteside et al., the hit height of the FP can be calculated from the following formula: 125 cm (the height of FP when sitting in the wheelchair) × 150% = 187.5 (cm). From this figure, it is considered that 73.6 (cm) is insufficient from 261.1 (cm), which is considered to be the hitting height required for a successful flat serve that requires a linear orbit. Therefore, the fact that a slight slice-spin was added to the FP's flat serve could be a reason why the results show no difference between the flat and slice serve speeds. On the other hand, significant differences in ball speed were observed between the flat and kick, and the slice and kick. Although the present study did not record the kinematics data on each serve, we hypothesized that the FP swung the racket vertically during the kick serve from below, providing a lower speed and higher spin rate.

4.2 Average spin rate of the three types of serve in each group

Focusing on the quantified value of the average spin rate of various serves, the average spin rate was higher in the order of the kick, slice, and then flat in all groups except for wheelchair tennis players, FJr, MP, and FP (Table 3). Many studies have been published focusing on ball speed as an indicator to evaluate serve performance (Adachi, 1999; Cross and Pollard, 2009; Maquirriain et al., 2016; Wong et al., 2014). However, ball speed alone is insufficient to assess the factors that make up the quality of the serve (Kreighbaum and Hunt, 1978) or the serve performance. Sakurai et al. (2013) identified the spin rate and axis of rotation in the serves of elite tennis players. They reported that the spin rate and axis of rotation affect the speed and trajectory of the ball and that there is a trade-off between speed and spin rate. The reason for this is because the server is given two opportunities to serve, giving no points to the opponent for the serve miss in the first serve (JTA Tennis Rulebook, 2020), therefore the first serve is often struck with a fastball-type flat serve with little rotation. In the second serve, however, an error serve will lead to conceding a point to the opponent's score, therefore it is necessary to avoid netting out and to make sure that the ball lands in the service box. To do so, the player must give the ball a lot of rotation and hit a safe and accurate serve (slice, kick). To be a top player, deciding what kind of serve to hit according to the situation of the match is an important factor in advancing the match. In this study, the spin rate of the serve of the top-level Japanese players tended to be higher in the order of kick, slice, and then flat. This result suggests that the type of serve can be inferred from the spin rate, and this data may be utilized as an index for evaluating serve performance. A characteristic feature of the results of this study is that wheelchair tennis players (MP and FP) showed a higher spin rate in a flat serve. Since it has been reported that there is a correlation between height and serve performance (Vaverka and Cernosek, 2013) and increasing the hitting point height improves serve performance and increases the margin of allowable error (Brody, 1987), for wheelchair tennis players, who have a limited trunk motion, and consequently, the hit height is lower than able-bodied players (Cavedon et al., 2014), this will be a disadvantage affecting their serve performance. For these reasons, MPs and FPs emphasize the upward swing of the racket to avoid netting out, which can lead to a higher top-spin even on a flat serve. In addition, the value of the kick in MP had the same value as the kick in MJr. Also, the fact that MP's kick value was higher than that of able-bodied players (FPro, FU, and FJr) is thought to indicate the high level of MP's hitting skill. Normally, hitting the ball from a wheelchair would be difficult to obtain the ground reaction force (GRF) (Elliott and Wood, 1983), which encourages a vertical racquet swing, because lower-limb loading techniques cannot be used. However, MP may have been able to generate high RPMs by controlling their center of gravity, such as by floating their backrest or one of their tires after hitting the ball, this being a unique hitting technique that replaces the energy flow of the lower extremities in able-bodied players. The post-impact behavior caused by the kick aims to lead to a misjudgment and hitting error by the receiver. The accuracy of the kick is also considered to be an important factor in determining the winner. Utilizing the results in Muramatsu et al. (2010, 2015), we acquired data by having subjects hit three types of serves (flat, slice, and kick) with maximum effort. This result, which quantified the spin rate of the three types of serves of Japanese top-level tennis players, is considered to be an important index for evaluating serve performance.

4.3. Relationship between ball speed and spin rate

Focusing on the relationship between the ball speed and spin rate in each group, the regression line of MPro, which has a high competition level, was distributed at the top right of the graph, followed by in the order of MU, MJr, FPro, MP, FU, FJr, and then FP (Fig. 2). Our results suggest that the relationship between the speed and spin rate is related to the player's competition levels among the national top level players, which was consistent with previous findings on the world's top players studies on the ball speed and spin rate of serves reported by Muramatsu et al. (2015). The data analyzed in these studies was a partial extract of the actual match and does not take into account strategic bargaining in the match. In other words, in an actual game, the 1st serve is not always hit with a fast ball because players bargain with the opponent. In some cases, the 2nd serve, which requires a high success rate, is not hit with a rotating system. With regard to these issues, their studies are not strictly controlled. Judging from these previous studies, this is the first study to provide new evidence that the value derived from the serve speed and the spin rate is located in the upper right of the curve. However, the regression lines between FU and FJr were shown at almost the same position. We propose the unique playing style of Japanese female players. The main court surface used in student and junior tournaments held in Japan is artificial grass with sand. The coefficient of restitution of artificial grass with sand is 0.66 (Sumitomo Rubber Industries, Ltd.), and it is characterized in that the ball bounce is lower than that of the hard or clay court. In other words, Japanese women's tennis players regularly may put more emphasis on the practice of strokes than serves, because the serve's strength diminishes due to the influence of the court surface. However, in the case of FPro, who has participated in the Olympics, as the position of the regression line clearly shows the upper right, to win in the world's four major tennis tournaments (i.e., Australia, France, England, and United States), serve speed can be considered to be a major factor in winning and losing. Taking these findings into consideration, the serve performance including speed and spin rate should be improved among Japanese female tennis players to win in the world's tournaments. In addition, the regression line of MP was located at the upper right position compared to that of FU and FJr. This finding indicates a higher serve performance in MP than in FU and FJr.

4.4. The number of trials required to achieve the task

Focusing on the number of trials required to achieve the task in each group, no significant difference was found between MPro and FPro. On the other hand, in the other groups, significant differences were observed between the flat and slice, the flat and kick, or the slice and kick (Figs. 3 and 4). The challenges set in this experiment were as follows: the flat and kick to the center direction (T zone), and the slice to the wide direction with maximum effort and into the target area (width 1 m, length 2 m). They were required to hit five balls for each serve (flat: 5 balls, slice: 5 balls, kick: 5 balls), meeting the conditions required for each type of serve. These conditions were set as tasks with great difficulty. In the study by Kovacs and Ellenbecker (2011), the experiment was attempted by classifying the period from the start to the completion of the serve into eight periods. The eight periods were: (A) start, (B) release, (C) loading, (D) cocking, (E) acceleration, (F) impact, (G) deceleration, and (H) completion. The ability to control spacing (special aspects), grading (strength competence), and timing (temporal aspects), and to reproduce stable movements are all important aspects for successful serves. Especially for the flat serve, as it is an aggressive ball-hitting technique that requires a low number of rotations, it can be considered that delicate racket operation in the impact phase is the key to success. Slice and kick are often used in the second serve, which is a spin type of serve, and has slightly defensive characteristics compared to the flat serve. Considering these results comprehensively, in the groups other than MPro and FPro (MU, MJr, FU, FJr) except for MP and FP, which are special cases of wheelchair tennis, the number of trials required for the flat serve was the highest value. Therefore, we suggest that this data reflects the difficulty and accuracy of the serve hitting technique. In addition, the fact that there was no significant difference in the number of trials required to achieve the task between MPro and FPro reflects the high accuracy and stability of the serve of professional tennis players who play at the world's top level. Guillot et al. (2013) confirmed the effectiveness of motor imagery combined with physical exercise to improve tennis serve performance. The reason why MPro and FPro showed high success rates might be that they were systematically aware of each process from (A) to (H), start to completion, classified by Kovacs and Ellenbecker (2011). It is plausible that they were serving with good motor imagery. In this study, measurements, such as Movement Imagery Questionnaire (MIQ-R; Hall and Martin, 1997; Lorant and Nicolas, 2004) were not performed, but including this variable is a future research agenda.

5. Conclusion

The present study investigated the characteristics of flat, slice, and kick serves in Japanese top-level tennis, including male and female professional players, university and junior top players, and Paralympian wheelchair players. The approximate curve obtained from the speed and spin rate, and the accuracy for serves were dependent on the competition level. Based on these findings, data feedback to the players would be important to promote self-understanding of their serving skills with correcting the gap between the players' subjective and objective evaluation. This study suggests an index that can improve the serve performance of top-level tennis players and all recreational tennis players.

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