MECHANICAL ENERGY FLOW OF THE TRUNK IN TENNIS SERVE

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The purpose of this study was to investigate the mechanical energy flow of the trunk during tennis serve. Three-dimensional coordinates of the players performing flat, kick, and slice serves were collected. The findings were summarized as follows.1) Regardless of the spin characteristics, the mechanism that right arm acquires the mechanical energy is almost same. 2) It is important to rotate the trunk as fast as possible, when the more mechanical energy flows from the trunk to the right arm more. 3) The roles of both legs are different from the viewpoint of energetics. The lower trunk aqcuired the translational energy from the left leg mainly, and the rotational energy from the right leg mainly. And it is guessed that player selects preferentially not to flow the more mechanical energy to right arm but to swing a racquet appropriately (to generate a ball spin).

KEY WORDS: translational energy, rotational energy, characteristics of the ball.

INTRODUCTION: The serve is a key shot in a tennis match, because the serve is the only closed skill, and serve starts every point. Adachi (1999) reported that the first serve speed of players who moved on a next round in a tornament stayed fast and consistent throughout the tournament. Thus, most previous researches of the tennis serve have focused on the mechanism to generate the racquet or ball speed in flat serve (e.g. Sprigings, Marshall, Elliott, & Jennings, 1994). On the other hand, Sato, Eguchi, Iwashima, Kubota, Iwamoto, & Umebayashi (2003) investigated the strategy of serve game in men’s singles at the first round and second round in Australia Open 2001. They reported that it was more effectual to use a change-up first serve and to make the combination with various serve speeds in order to keep the serve game for the players who can hit even high-speed first serves over 200km/h. Sheets, Abrams, Corazza, Safran, & Andriacchi (2011) investigated differences in upper body movement patterns that distinguish the difference among flat serve (FL), kick serve (KC), and slice serve (SL) techniques in the same subject. In general, it is advantageous to adding heavy spin or to hitting high speed serve that we can get large head speed. It is almost equivalent to the large kinetic energy that the racquet speed is large. Futhermore, the mechanical energy is said to flow from lower limbs to upper limbs during the serve motion. However, the literature concerning the mechanical energy flow in tennis serve is limited. Furthermore, It is necessary to measure the rotation of the ball to evaluate KC and SL, while most of previous researches about KC and SL do not measure the ball spin. Therefore, it is important to analyze the relations of ball characteristic (speed and spin) and the mechanical energy flow during serve at the same time. The purpose of this study was to investigate the mechanical energy flow of the trunk during serve.

METHODS: Eight right-handed male university tennis players (Height: 1.72±0.03m, Body mass: 66.2±5.4kg) participated in this study. The stance of all players was foot back. We constructed the makeshift tennis court that based on the International Tennis Federation‘s regulation on the experiment floor, and set the target area of 1m in width from the center serve line on the service box (Figure 1-a). Three-dimensional coordinates data of the players performing FL, KC and SL were collected using a motion capture system (Vicon MX, Oxford Metrics Inc., UK) at 250Hz. In a similar way, three-dimensional coordinates data of the reflective markers on the ball were collected at 500Hz. Note that, the X-axis was defined as a parallel unit vector of the baseline (a direction toward the deuce side is positive). The Z-axis was defined as a vertical unit vector (an upper direction is positive). The coordinate data were smoothed using a Butterworth low-pass filter with optimal cut-off frequencies, which were determined by the residual error method (Winter, 1980). Take back was defined as a instant when the CG of the body reached its lowest point. The time from take back to ball impact was analyzed. We calculated each kinematic parameter with 15 segment model. The ball center was estimated from the reflective markers of ball by the least-square method. The ball speed was calculated from the coordinate value of the ball center. The angular velocity vector of the ball (the number of rotations of ball) were calculated from the time changes of the movement coordinate system fixed on the ball. The lean angle of the rotation axis of the ball was defined as the angle between Z-axis and the angular velocity vector that was projected on an X-Z plane (Figure 1-b). The mechanical power (a time rate of change of mechanical energy) acting on upper/lower trunk and generated/absorbed in each joint were divided into the following terms. 1) $\mathrm{JFP_{trn}}$: a time rate of change in the translational energy due to the joint force. 2) $\mathrm{JFP_{rot}}$: a time rate of change in the rotational energy due to the moment of joint force. 3) STP: a time rate of change in the rotational energy due to the joint torque. 4) JTP: a time rate of change in the mechanical energy of the system (whole body) due to the joint torque.

$$\mathrm{JFP_{trn}} = \boldsymbol{v_{cg}} \cdot \boldsymbol{F}.$$
$$\mathrm{JFP_{rot}} = \boldsymbol{\omega_{seg}} \cdot (\boldsymbol{r_{CG\rightarrow jnt}} \times \boldsymbol{F}).$$
$$\mathrm{STP} = \boldsymbol{\omega_{seg}} \cdot \boldsymbol{T}.$$
$$\mathrm{JTP} = \boldsymbol{\omega_{jnt}} \cdot \boldsymbol{T}.$$

Where, $\boldsymbol{r_{cg\rightarrow joint}}$ is a vector from a segment CG to joint, $\boldsymbol{v_{cg}}$ is a CG velocity vector of a segment, $\boldsymbol{\omega_{seg}}$ is an angular velocity vector of a segment, $\boldsymbol{F}$ is a joint force vector acting on a segment, $\boldsymbol{T}$ is a joint torque vector acting on a segment, $\boldsymbol{\omega_{jnt}}$ is an angular velocity vector of a joint. The each power was integrated to show the change in the mechanical energy of a segment. Note that, translational and rotational energy (summation of $\mathrm{JFP_{rot}}$ and STP) that were transferred to the upper and lower trunk were divided into each direction component of moving coordinate systems (forward-backward, rightward-leftward, and upward-downward) fixed on upper and lower trunk.

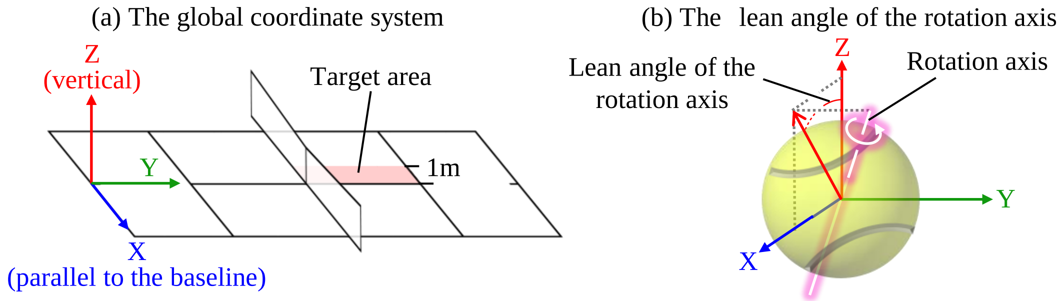

Figure 1: Definition of the global coordinate system and the lean angle of the rotation axis.

RESULTS: Table 1 shows the kinematic parameter of the ball at the ball impact. The ball speed of FL was largest and that of KC was smallest. On the other hand, the number of ball rotation of KC was largest and that of FL was smallest. The lean angle of the rotation axis in KC was more horizontal than that of SL.

Table 2-a shows the mechanical energy that was generated in each parts. Regardless of the spin characteristics, the mechanical energy was mainly generated by the both legs (in particular the left leg contributed most). Both legs generated 70-80% of the total increment of mechanical energy. The remaining increment of mechanical energy (about 20%) was almost

Table 1
Ball parameter.

	Speed [km/h]	Number of rotations [rps]	Lean angles of rotation axis [deg]
FL	180.9±12.6	18.3±7.0	6.8±13.1
KC	126.9±14.1	62.9±7.9	36.1±4.3
SL	161.5±15.8	39.5±9.5	14.5±6.8

* : p<0.05 ***: p<0.001

Table 2
Evolution and flow of mechanical energy.

(a) Generated mechanical energy in each parts.

	Torso & Neck	Right Leg	Left Leg	Right Arm	Left Arm
FL	0.16±0.18	2.04±0.46	2.90±0.51	0.17±0.19	1.09±0.29
	(2.5%) *	(32.1%)	(45.6%)	(2.6%) *	(17.1%)
KC	0.05±0.17	1.92±0.69	3.02±0.40	0.43±0.18	0.98±0.27
	(0.8%)	(30.0%)	(47.1%)	(6.8%)	(15.3%)
SL	0.12±0.16	2.09±0.63	2.93±0.36	0.31±0.17	1.07±0.22
	(1.9%)	(32.1%)	(44.9%)	(4.7%)	(16.4%)

(b) Mechanical energy flow from upper trunk to right arm.

	Translational energy			Rotational energy		
	Forward-Backward	Rightward-Leftward	Upward-Downward	Flexion-Extension	Right-Left bending	Right-Left rotation
FL	0.21±0.14	0.60±0.27	0.32±0.03	0.34±0.14	0.46±0.11	1.93±0.37
	(5.4%)	(15.6%) *	(8.3%)	(8.9%)	(11.9%)	(50.0%) **
KC	0.20±0.10	0.46±0.17	0.35±0.05	0.32±0.13	0.50±0.07	1.54±0.35
	(5.9%)	(13.6%)	(10.4%)	(9.6%)	(14.8%)	(45.8%) **
SL	0.22±0.12	0.58±0.23	0.33±0.04	0.37±0.15	0.45±0.10	1.87±0.44
	(5.9%)	(15.1%)	(8.7%)	(9.8%)	(11.8%)	(48.8%)

(c) Translational energy flow from leg to lower trunk.

	Right hip			Left hip		
	Forward-Backward	Rightward-Leftward	Upward-Downward	Forward-Backward	Rightward-Leftward	Upward-Downward
FL	0.08±0.07	0.27±0.29	0.48±0.23	0.38±0.21	0.21±0.23	1.72±0.08
	(2.4%)	(8.6%)	(15.2%)	(12.0%) ***	(6.6%)	(55.1%)
KC	0.04±0.03	0.25±0.27	0.56±0.32	0.51±0.24	0.14±0.15	1.73±0.08
	(1.3%)	(7.9%)	(17.2%)	(15.7%) ***	(4.4%)	(53.6%)
SL	0.04±0.03	0.28±0.28	0.50±0.21	0.37±0.17	0.16±0.14	1.74±0.09
	(1.3%)	(9.1%)	(16.2%)	(12.0%)	(5.2%)	(56.1%)

(d) Rotational energy flow from leg to lower trunk.

	Right hip			Left hip		
	Flexion-Extension	Right-Left bending	Right-Left rotation	Flexion-Extension	Right-Left bending	Right-Left rotation
FL	0.11±0.05	0.40±0.10	0.95±0.32	0.19±0.12	0.15±0.10	0.66±0.15
	(4.6%) *	(16.2%)	(38.6%) ***	(7.9%)	(6.0%) *	(26.8%)
KC	0.08±0.05	0.43±0.13	0.63±0.25	0.14±0.06	0.21±0.12	0.59±0.17
	(3.6%)	(20.8%)	(30.3%) *	(6.6%)	(10.2%)	(28.5%)
SL	0.10±0.06	0.47±0.17	0.83±0.31	0.20±0.09	0.18±0.11	0.62±0.15
	(4.1%)	(19.6%)	(34.4%)	(8.3%)	(7.6%)	(26.0%)

* : $p<0.05$ ** : $p<0.01$ *** : $p<0.001$ (J/kg)

generated by the left arm. The increment of mechanical energy by the torso and neck in KC was smaller than that of FL, and increment of mechanical energy by right arm in KC was larger than that of FL.

Table 2-b shows the mechanical energy flow from upper trunk to the right arm. The rotational energy is total of STP and $\mathrm{JFP_{trn}}$. Regardless of the spin characteristics, the right arm acquired the mechanical energy by decreasing the rotational energy of the upper trunk (about 70%). Especially, the upper trunk rotational energy around right-left rotation decreased most (about 50%). The decrement of upper trunk rotational energy around right-left rotation axis of KC was the smallest (there was no significant difference). Moreover, the decrement of upper trunk translational energy of rightward-leftward was smaller than FL.

Table 2-c shows the translational energy flow from the both legs to the lower trunk. Regardless of the spin characteristics, the lower trunk acquired the translational energy mainly from the left hip. Most of the translational energy that the lower trunk acquired were the upward-downward component (especially from left hip).

Table 2-d shows the rotational energy flow from the legs to the lower trunk. Regardless of the spin characteristics, the lower trunk acquired the rotational energy mainly from the right hip except for KC. Most of the rotational energy that the lower trunk acquired were around the right-left roation axis (especially from right hip except for KC).

DISCUSSION: FL had the smallest number of rotations of the ball and the highest ball speed. The rotation axis of KC was more horizontal than SL. This means that players of this study were able to control the spin characteristics of the ball.
Regardless of the spin characteristics, the mechanical energy was mainly generated by the both legs and left arm. The right arm acquired the mechanical energy by decreasing the rotational energy of the upper trunk, particularly the upper trunk lost the rotational energy around right-left rotation axis the most. It can be considered that the mechanism of the mechanical energy flow during serve motion is similar (regardless of the spin characteristics). The right arm acquired the mechanical energy from the upper trunk by decreasing the left rotation of upper trunk. Thus, it is important to rotate (leftward rotation) the trunk as fast as possible by the leg action.The lower trunk acquired the rotational energy mainly from the right leg. On the other hand, the lower trunk acquired the translation energy mainly from the left leg. This suggests that the roles of the left and right leg are different. As for the translational energy that the lower trunk acquired, the upward-downward component was the largest. This energy originates the jump movement just before the ball impact. It is thought that the most of this energy are finally converted into the potential energy of the whole body. Thus, this energy would be related to the obtainment of the amount of height of impact point rather than the obtainment of the swing speed.
The translational energy of forward-backward component that flows from the left hip to the lower trunk in KC was larger than FL and SL. On the other hand, the rotational energy around right-left rotation axis that flows from the right hip to the lower trunk in KC was smaller than FL and SL. Murata & Fujii (2013) reported that it is necessary to generate a ball spin to avoid the head-on collision of a ball and the racquet (the ball hit against the racquet face vertically). Therefore, players changed the swing direction into rightward. Furthermore, the difference of swing direction was mainly caused by the posture changes of upper trunk (in particular player suppress the left rotation in KC and SL). From the results, it is inferred that player selects preferentially not to flow more mechanical energy to the right arm but to swing racquet for the appropriate direction (to generate the ball spin).

CONCLUSION: Regardless of the spin characteristics, the mechanism that right arm acquires the mechanical energy is almost same. It is important the both legs rotate (left rotation) the trunk as fast as possible. The roles of both legs are different from the viewpoint of energetics. It is guessed that player selects preferentially not to flow more mechanical energy to the right arm but to swing racquet appropriately. However, in the future it is necessary to investigate the serve motion of the different stance, because postural difference of lower limbs is largely depends on a stance.

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