Three-dimensional analysis of mechanical power flow
in the upper limb during tennis serving

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INTRODUCTION
Since the service is one of the most important shots for winning tennis games, coaches aim to achieve a more powerful service in players. For this reason it is important to clarify the serving mechanism kinematically and kinetically. However, most reported studies of tennis service have used the kinematical analysis method, and few reports have focused on kinetic parameters such as joint force, joint torque and mechanical power. The purpose of this study was to investigate three-dimensionally joint force, joint torque and mechanical power of the upper limb during tennis serving, and to examine the relationship between mechanical power flow and service speed.

METHODS
The subjects were 62 male tennis players: one professional tennis player and 61 university level players. They were requested to serve the ball as fast as they could, and at the same time the serving motion was videotaped using two high-speed video cameras at 200 frames/s. The transformation from digitized two-dimensional data to real-life three-dimensional coordinate data was conducted using the DLT method. The joint force and joint torque in the wrist, elbow and shoulder were determined by Winter’s link segment model (Winter 1990). The mechanical power resulting from the joint force (joint force power: JFP) and from the joint torque (joint torque power: JTP) was calculated using the equations

\[ JFP = F_x \cdot V_x + F_y \cdot V_y + F_z \cdot V_z \]

\[ JTP = T_x \cdot \omega_x + T_y \cdot \omega_y + T_z \cdot \omega_z \]

where \( x, y, z \) are the three axes of joint coordinate system fixed at the center of each joint, \( F \) is the joint force, \( V \) is the linear velocity of the segment endpoint, \( T \) is the joint torque, and \( \omega \) is the angular velocity of the joint. Finally, each mechanical work done by JFP and JTP were obtained by integrating JFP and JTP with time, respectively.

RESULTS AND DISCUSSION
1) Joint force power
Figure 1 shows the curves of JFP and JTP in each joint in typical examples of a fast server and a slow server (from the top wrist joint, elbow joint and shoulder joint). The JFP transferred from the proximal to the distal segment was markedly larger than the JTP in each joint, and the peak JFP (∫) appeared from the proximal to the distal joint with passage of time, regardless of the skill level. However, the peak JFP (shoulder: \( r=0.645; p<0.001 \), elbow: \( r=0.692; p<0.001 \), wrist: \( r=0.647; p<0.001 \)), and the mechanical work originating from the JFP (shoulder: \( r=0.589; p<0.001 \), elbow: \( r=0.706; p<0.001 \), wrist: \( r=0.645; p<0.001 \)) were both correlated significantly with the service velocity. These results suggest that the increase of mechanical energy in the distal segment occurs through inflow of JFP from the proximal segment. Thus, a fast server transfers JFP more efficiently from the proximal to the distal joint than a slow server.
Fig. 1 The curves of the joint force powers (blue) and joint torque powers (red) in the wrist, elbow and shoulder joints in typical examples of a fast server and a slow server.

2) Shoulder joint

JTP in three axes for the fast server and slow server are shown in Figure 2 (from the top wrist joint, elbow joint and shoulder joint). The positive mechanical work in the shoulder joint calculated from the JTP during the forward arm swing phase showed significant negative correlation with the service speed ($r = -0.269$; $p < 0.05$). Although most players produced positive JTP by internal rotation of the upper arm prior to impact, players with a very low service velocity produced positive JTP by horizontal adduction and abduction of the shoulder. More negative mechanical work produced by internal rotation torque resulted in a higher service velocity ($r = 0.589$; $p < 0.001$). The peak JTP by internal rotation (→) showed a positive correlation ($r = 0.645$; $p < 0.001$) with racket velocity. It is well known that muscle produces high mechanical power during a stretch shortening cycle (Bosco et al., 1981, Bosco et al., 1982). The above result showed that a fast server might efficiently produce JTP by a stretch shortening cycle of muscle during internal rotation movement. Overall, these results indicate that players with a high service velocity carry out simple arm movement in order to effectively exchange the translational segment movement to the rotational segment movement, and utilize the stretch shortening cycle to produce the high power.

3) Elbow joint

In the elbow joint, the mechanical work produced by extension torque during the first half of the elbow extension movement was considerably small, and there was a significant negative correlation between the magnitude of this work and service velocity ($r = -0.309$; $p < 0.05$). This suggests that the elbow extension
movement is generated mainly by JFP transferred from the upper arm, and that a fast server utilizes JFP more efficiently than a slow server. Thereafter, negative JTP followed by positive JTP was observed during the elbow extension movement. The former negative JTP played a role in preventing any elbow hyperextension generated by transfer of the JFP from the upper arm, and the positive JTP cancelled the elbow flexion torque generated by the JTP originating from the wrist ulnar flexion torque. That is, the torque in the elbow joint did not play a role in accelerating the service velocity, but in transferring the JFP from the upper arm to the forearm efficiently to obtain a high service velocity, and also to keep the impact point high.

4) Wrist joint
Although the positive JTP of wrist palmar flexion was observed prior to impact, no significant correlation was obtained between the positive work by JTP and service speed. However, the peak JTP of wrist palmar flexion (→) showed a significant positive correlation with racket speed (r=0.354; p<0.01). These results suggest that a fast server utilizes the power flow from the proximal segment more efficiently, and also generates positive palmar flexion power during the palmar flexion movement immediately before ball impact.

![Diagram of joint torque powers](image)

Fig.2 The curves of the joint torque powers on the joint coordinate system fixed at the center of wrist, elbow and shoulder joints in typical examples of a fast server and a slow server.

References
Winter, D. A. Biomechanics and motor control of human movement, 2nd Ed. John Wiley and Sons, 1990