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Trunk rotation torques through the hip joints during the one- and two-handed backhand tennis strokes

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Abstract
The aim of the present study was to compare kinetically the roles of the lower extremities in generating trunk rotation in the tennis one-handed and two-handed backhand strokes. Fourteen male collegiate tennis players, seven with a preference for the one- and seven with a preference for the two-handed technique, were recruited as participants. The motion of each backhand stroke was filmed using two high-speed cine-cameras, and the ground reaction forces on the feet were measured separately using two force platforms to determine the joint moments and joint reaction forces at the hip, knee and ankle joints. A significant difference in hip joint moments between the two types of stroke was found in the phase from the start of forward rotation of the pelvis to the start of racket forward movement. For trunk rotation, the one-handed backhand players exerted a large joint moment in the front leg, whereas the two-handed backhand players exerted a large joint moment in the back leg. The exertion of a large hip joint moment in the latter stroke was comparable with the exertion in a forehand stroke reported previously.

Keywords: Backhand stroke, kinetics, pelvic torque, tennis

Introduction
Elliott (2000) stated that trunk and leg rotation are important in powerful hitting movements such as hockey penalty stroke and baseball batting. It has also been stated in tennis textbooks that trunk rotation is an important power source for ground strokes. Early (1995) stated that hip and shoulder rotations were the most significant source of power for ground strokes, a view supported by Groppel (1992). Moreover, Bahamonde (1999) reported a relationship between trunk rotation and racket velocity and stated that “one of the most important elements of the forehand and backhand strokes was the development of optimal trunk rotation” and that “trunk rotation was highly correlated with the racket velocity”.

Elliott, Marsh and Overheu (1989) reported that the shoulders rotated forward through an angle of 95° from a backswing position to ball impact. Iino and Kojima (2001) reported that the shoulders and the pelvis rotated 98° and 60° respectively from the completion of the backswing to ball impact in forehand ground strokes. It is therefore logical to assume that approximately 60% of shoulder angular displacement is derived from pelvic angular displacement. This suggests that the lower extremities may play an important role in trunk rotation.

Although a number of papers have clarified kinematically the roles of the racket arm and the trunk in the tennis forehand ground stroke (Bahamonde, 1999; Elliott et al., 1989; Takahashi, Elliott, & Noffal, 1996), there has been little research on the roles of the lower extremities in generating trunk rotation. Recently, Iino and Kojima (2001, 2003) investigated kinetically the roles of the lower extremities in generating a forward pelvic rotation in the tennis forehand ground stroke and reported that the extension moment at the hip joint of the back leg was important for the rotation.

The one-handed and two-handed strokes are two varieties of the tennis backhand stroke. Several researchers (Elliott & Christmass, 1995; Elliott et al., 1989; Giangarra, Conroy, Jobe, Pink, & Perry, 1993; Reid & Elliott, 2002) have studied the backhand ground stroke in an attempt to clarify the role of the racket arm or to describe basic stroke mechanics kinematically. Elliott et al. (1989) studied down-the-line and cross-court topspin backhand drives and running down-the-line backhand drives of elite tennis players. Reid and Elliott (2002)
examined differences in the one- and two-handed tennis backhands when hit flat across-court and down-the-line, and with heavy topspin down-the-line. Though many basic kinematic descriptions were reported by these studies, no objective information is available on generating trunk rotation.

The large trunk rotation observed in backhand ground strokes (Elliott et al., 1989) suggests that the role of the lower extremities is important for trunk rotation. Since there is a paucity of data on the roles of the lower extremities in generating trunk rotation in the tennis backhand stroke, the aim of the present study was to compare kinetically the roles of the lower extremities in generating trunk rotation in the one-handed and the two-handed tennis backhand strokes.

**Methods**

Fourteen right-handed male Division 1 collegiate tennis team players in the Tokyo Prefecture region were recruited as participants. The participants' physical characteristics were as follows: age $20.4 \pm 1.8$ years, height $1.73 \pm 0.04$ m, body mass $65.1 \pm 6.0$ kg (mean $\pm s$). All participants signed an informed consent document before participating in the study. Half of the participants performed their preferred one-handed backhand strokes and the other half performed their preferred two-handed backhand strokes. All players used a closed stance with both backhand techniques.

As a ball server, a long inclined flute was devised to reduce variation of the contact points between the racket and the balls during strokes. An experimenter placed a ball at a certain position on the flute and this enabled the ball to be projected such that each participant could hit the ball after it bounced on the floor. The position of the server was carefully adjusted to each participant's preferred position to ensure that he was able to perform his best stroke. The net was located 11.9 m from the hitting position. The participants were asked to hit a topspin shot perpendicular to the net with their own rally-paced ball speed and enough depth for a baseline shot.

Before being filmed, each participant was permitted as much practice as required to become accustomed to the experimental system. The participants assessed their own strokes in terms of ball speed and depth. The shot considered the best by each participant was used for analysis. If a participant assessed more than one shot to be successful and it was difficult to judge which was the better of the two, the later shot was selected for the analysis.

Three strokes for each participant were filmed using two phase-locked high-speed cine cameras (1PL, Photo-Sonics) at a nominal speed of 200 frames per second. Three strokes were sufficient for all participants to play at least one acceptable stroke for analysis. The ground reaction forces of both feet during the stroke were measured separately using two force platforms (type 9281B, Kistler) with a sampling rate of 400 Hz. Electrical signals were used to synchronize the films with the ground reaction forces. Each ground reaction force was normalized with respect to each participant’s body mass.

Five styrol spheres with a diameter of 3 cm were used as markers for the movement of the racket. One was placed on the tip of the racket (racket head) and the rest on the upper and lower sides of the racket. Figure 1 shows a representative one-handed backhand stroke with the markers in place.

Black adhesive tape 19 mm wide was wrapped around the ankle and knee joints of the participant to estimate each joint centre. The tape covered certain anatomical landmarks around each joint. The lateral and medial femoral epicondyles were used as the landmarks for the knee joints, and the lateral and medial malleoli as the landmarks for the ankle joints. To assess the rotation of the shanks and thighs, styrol spheres with a diameter of 2 cm attached to each end of hand-made aluminium frames were fixed on the body segments (Figure 1).

The left and right anterior superior iliac spines were also marked with the same type of styrol spheres. A belt with four styrol spheres of the same type was wrapped horizontally around the pelvis (Figure 1).

Three-dimensional coordinates of these markers and the joint centres of the lower extremities were reconstructed using the direct linear transformation method (Adel-Aziz & Karara, 1971). These coordinates were filtered using a fourth-order zero-lag Butterworth low-pass digital filter (Winter, 1990). The cutoff frequencies of the filter for each marker

![Figure 1. A one-handed backhand stroke performed by one of the participants. The locations of the markers on the racket and the player are shown.](image-url)
and each joint centre were determined by residual analysis (Winter, 1990).

Local coordinate systems were constructed for the pelvis and the right and left feet, shanks and thighs using the positions of the markers (Figure 2). For the feet, shanks and thighs, the longitudinal axes of the segments were set as their Z axes. The Y axes of the feet were determined using the vector product of the unit vectors for the Z axes of the foot and shank. The Y axes of the shanks and thighs were also determined using the vector product of the unit vectors for the Z axes of the shank and thigh. The X axes of the feet, shanks and thighs were determined using the vector product of the unit vectors of the Y and Z axes of each segment.

For the pelvis, three orthogonal axes were defined in the following way (Figure 2). The origin of the coordinate system of the pelvis was defined as the midpoint of the right and left hip joint centres. The superior–inferior axis was vertical to the ground when the participant was standing upright. The medial–lateral axis was the line joining the left and the right hip joint centres. The anterior–posterior axis was determined using the vector product of the unit vectors for the superior–inferior and medial–lateral axes. These axes were determined using the markers on the belt during each stroke.

To estimate the hip joint centres, the coefficients of Bell, Pederson and Brand (1990), as determined using the method of Tylkowski, Simon and Mansour (1982), were used. The positional relationship between the local coordinate system of the pelvis and the spheres on the belt was determined with the participant standing upright. The coordinates of the pelvis and the position of the left and right anterior superior iliac spines during the strokes were estimated from the coordinates of the spheres on the belt.

In this study, the term “pelvic rotation” was defined as the rotation around the superior–inferior axis. The medial–lateral axis was projected onto a horizontal plane, and the term “pelvic angle” was defined as the angle between the projected medial–lateral axis and the direction of the flight of the ball. The angular velocity of the pelvis was determined using numerical differentiation of the pelvic angle data.

The lower extremities were modelled as a link segment model comprising the rigid feet, shanks and thighs. The joint moments and joint reaction forces at the ankle, knee and hip joints were determined using the inverse dynamics approach (Bresler & Frankel, 1950; Vaughan, Davis, & O’Connor, 1992). The mass and the position of the centre of mass for each segment were estimated using the coefficients of Dempster (1955) in Miller and Nelson (1973). The moment of inertia of each segment was determined using the regression equations of Chandler, Clauser, McConville, Reynolds and Young (1975).

The angular velocities of the shanks and thighs were determined with transformation matrices that were calculated using the positions of the three markers on each segment (Veldpau, Woltring, &

![Figure 2. The local coordinate systems constructed for the pelvis and the lower extremities.](image-url)
The angular accelerations of the segments were determined by numerical differentiation of the angular velocities.

The moment due to the joint force at each hip joint was calculated using a vector product of the joint force vector and the position vector of the hip joint centre with respect to the origin of the pelvis. The joint moments and the moments due to the joint forces at both hip joints contribute to rotate the pelvis around the superior–inferior axis. The vectors of these moments were projected onto the superior–inferior axis. The sum of the projected vectors was referred to as pelvic torque after Dortmans, 1988). Each projected vector was referred to as a contributory component of the pelvic torque and each moment as a component of the pelvic torque (Figure 3).

The joint moment vector at each hip joint was projected onto the X, Y and Z axes of the ipsilateral thigh. The projected vectors on the X, Y and Z axes corresponded to the moments of extension/flexion, abduction/adduction and internal/external rotation, respectively. As shown in Figure 3, they were referred to as anatomical components of the hip joint moment. The anatomical components of the hip joint moment were then projected onto the superior–inferior axis to determine the contribution of the hip joint moment to the pelvic torque in terms of anatomical joint moments (Figure 3). The projected anatomical components of the hip joint moment were referred to as contributory components to pelvic torque.

The position vector from the right hip joint to the racket head at ball impact was used to determine the racket position at the impact in consideration of the inter-individual differences in foot positions on the force platforms. The vector was projected onto the axis parallel to the direction of the ball hit on the horizontal plane. The length of the projected vector was used to define an index of the racket position at the point of impact with respect to the position of the right hip joint. The length was normalized relative to the height of each participant. The normalized length was referred to as the “racket position at ball impact”. The value of the racket position was positive when the impact point was in front of the right hip joint.

Swing time was defined as the time from the beginning of a racket backward movement up to the point of ball impact. A complete stroke was divided into the following three phases in terms of the movements of the pelvis and the racket:

- **Early backswing phase**: from the beginning of a racket backward movement up to the time when the pelvis stopped its backward rotation (completion of the backward rotation of the pelvis).
- **Late backswing phase**: from the completion of the backward rotation of the pelvis to the end of the racket backward movement (completion of backswing).
- **Forward swing phase**: from the completion of backswing to the point of ball impact.

The time when the pelvis stopped its backward rotation was determined from the pelvic angle. The time when a racket backward movement stopped was determined as follows:

1. The trajectory of a ball hit was projected to a horizontal plane, and then a line was extended backward from the projected trajectory.
2. The trajectory of the racket head tip was projected to the extended line.

![Figure 3. Schematic representation of the relationships among the hip joint moment, anatomical components of the hip joint moment and contributions of the anatomical components of the hip joint moment to pelvic torque. Each hip joint moment vector was projected onto the three orthogonal local coordinate axes of the thigh and the projected vectors were referred to as the anatomical component of the joint moments. The vectors of anatomical components of the hip joint moment were also projected to the superior–inferior (SI) axis of the pelvis and the projected vectors were referred to as contributions of the anatomical components of the hip joint moment to the pelvic torque. Pelvic torque consists of its contributory components (the moments about the SI axis due to the right and left hip joint moments and the right and left hip joint forces), and the vectorial sum of the contributions of the anatomical components of the hip joint moment to pelvic torque is one of the contributory components of pelvic torque.](image-url)
3. The time when the projected trajectory of the tip was the farthest from the impact point was defined as the completion of backswing.

The contributory components of the pelvic torque were integrated with respect to time over these three phases to quantify the contributions of the joint moments and the moments due to the joint forces to the pelvic rotation. The sum of the four integrated contributory components was considered as the action from the lower extremities on the pelvis to change the angular momentum of the pelvis about the superior-inferior axis in each phase. The contributions of the anatomical components of the hip joint moment to the pelvic torque were also integrated in the same way to assess their contributions to pelvic rotation.

The times of the three phases for each participant were normalized relative to the swing time to allow comparison of the results among participants. Normalized times of −1 and 0 represented the beginning of a racket backward movement and the point of ball impact, respectively. Two-way analyses of variance (stroke style × integrated contributory components, stroke style × integrated contributions of the anatomical components of the right hip joint, stroke style × integrated contributions of the anatomical components of the left hip joint) were performed for each of the three phases in terms of the movements of the pelvis and the racket. These analyses of variance were followed up with Tukey’s or Scheffe’s post-hoc tests if a significant interaction was observed.

Tukey’s multiple comparison tests were used to test for differences among the integrated contributory components in each stroke style (Nagata, 1998). The Tukey’s tests were also used to examine differences among the integrated contributions of the anatomical components of the hip joint moment to pelvic torque at each hip joint in each stroke style (Nagata, 1998). Scheffe’s multiple comparison tests were used to examine differences in the integrated contributory component of the joint moment, differences in the component of the joint forces, and differences in the integrated contributions of the anatomical components of the hip joint moment to the pelvic torque at each hip joint. Statistical significance for all tests was set at $P < 0.05$.

**Results**

**Racket head speed and racket position at ball impact**

The mean racket head speeds just before ball impact for the one-handed and two-handed strokes were $18.8 \pm 2.0$ and $18.9 \pm 3.7 \text{ m} \cdot \text{s}^{-1}$, respectively (mean ± s). The mean racket positions at ball impact in the one-handed and two-handed strokes of $0.044 \pm 0.072$ and $0.044 \pm 0.113$, respectively, were also similar.

**Swing time and normalized time**

The mean swing times of the one-handed and two-handed strokes were $0.52 \pm 0.14$ and $0.46 \pm 0.10 \text{ s}$, respectively. The normalized times of the beginning of the late backswing phase and the forward swing phase, and the normalized time when the peak pelvic torque was recorded, are shown in Table I. No significant differences were found between the one- and two-handed strokes.

**Ground reaction force**

Typical examples of ground reaction forces in the one-handed and two-handed strokes are shown in Figure 4. Transfer of body weight from the left leg to the right leg was observed during the forward swing of the strokes for all participants. The normalized peak vertical forces with respect to body weight in the one-handed strokes were $1.14 \pm 0.19$ and $0.83 \pm 0.15 \text{ N} \cdot \text{kg}^{-1}$ for the front and back leg respectively; for the two-handed strokes these values were $1.23 \pm 0.14$ and $1.00 \pm 0.08 \text{ N} \cdot \text{kg}^{-1}$, respectively. The normalized times when the peaks were recorded in the one-handed strokes were $-0.18 \pm 0.09$ and $-1.05 \pm 0.25 \text{ s}$ for the front

<table>
<thead>
<tr>
<th>Stroke</th>
<th>Swing time (s)</th>
<th>Time to end of the backward rotation of the pelvis</th>
<th>Time to end of the backward rotation of the racket</th>
<th>Time of peak pelvic torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-handed</td>
<td>0.52 ± 0.14</td>
<td>−0.77 ± 0.04</td>
<td>−0.36 ± 0.16</td>
<td>−0.32 ± 0.11</td>
</tr>
<tr>
<td>Two-handed</td>
<td>0.46 ± 0.10</td>
<td>−0.75 ± 0.07</td>
<td>−0.36 ± 0.21</td>
<td>−0.35 ± 0.13</td>
</tr>
</tbody>
</table>

Table I. Mean swing time and the normalized times at certain events (mean ± s)
and back legs, respectively; for the two-handed strokes these values were $-0.15 \pm 0.11$ and $-0.98 \pm 0.27$ s, respectively.

**Angular displacements of the knee joints**

The mean maximum and minimum knee joint angles of the right leg during the one-handed strokes were $172.0 \pm 5.2^\circ$ and $140.9 \pm 8.7^\circ$, respectively; for the left leg, these angles were $166.6 \pm 4.7^\circ$ and $146.5 \pm 4.8^\circ$, respectively. The mean maximum and minimum knee joint angles of the right leg during the two-handed strokes were $166.5 \pm 3.7^\circ$ and $139.7 \pm 7.2^\circ$, respectively; for the left leg, these angles were $157.2 \pm 7.8^\circ$ and $142.1 \pm 10.8^\circ$, respectively. The mean maximum angle of the left knee joint in the one-handed stroke was significantly larger than that in the two-handed stroke ($P = 0.04$).

**Pelvic angular kinematics**

Some angular aspects of the pelvic rotation are shown in Table II. The pelvic angle at the end of its backward rotation in the one-handed stroke was not different from the angle in the two-handed stroke. The angle at the point of impact in the one-handed stroke ($170.2 \pm 10.3^\circ$) was significantly larger than in the two-handed stroke ($153.2 \pm 12.5^\circ$). The range of angular displacement of the pelvis from the end of its backward rotation to the point of ball impact in the two-handed stroke ($54.4 \pm 9.0^\circ$) was significantly larger than that in the one-handed stroke ($31.4 \pm 8.3^\circ$). The mean angular velocity of the pelvis during the forward swing phase in the two-handed stroke ($9.4 \pm 3.4$ rad·s$^{-1}$) was significantly larger than that in the one-handed stroke ($4.9 \pm 1.9$ rad·s$^{-1}$).

**Joint moment components at the hip joints**

An example of the anatomical components of the hip joint moment during the two types of strokes is shown in Figure 5. A large adduction moment was observed during the late backswing phase and the forward swing phase at the right hip joint for both strokes. Just before ball impact, an extension
moment was observed as the adduction moment decreased at the joint (Figure 5b,d). A moderate abduction moment that turned into an adduction moment and an extension moment were observed at the left hip joint (Figure 5a,c). The patterns of these curves were common to both strokes and all players.

Contributions of the joint moments and joint forces at the hip joints to pelvic torque

An example of pelvic torque and its contributory components is shown in Figure 6. The peak pelvic torque of most participants was recorded early in the forward swing phase (Table I).

Mean values for the integrated contributory components of pelvic torque during the three phases are shown in Table III. Significant differences between the components were identified by ANOVA during all three phases. Analysis of variance also showed a significant interaction between the stroke styles and the components during the late backswing phase. Using post-hoc tests, many of the differences in mean values for each type of stroke and between the two types of strokes were found in the late backswing phase as follows:

- The integrated component due to the right hip joint moment in the one-handed stroke was larger
than the integrated component in the two-handed stroke, while the integrated component due to the left hip joint moment in the two-handed stroke was larger than the integrated component in the one-handed stroke.

- In the one-handed stroke, the integrated component due to the left hip joint force was smaller than the integrated component due to the right hip joint moment.
- The integrated component due to the left hip joint moment in the two-handed stroke was the largest of the integrated components in the two-handed stroke.

**Contributions of the components of hip joint moments to pelvic torque**

Mean integrated values of the contributions of the anatomical components of the hip joint moment to pelvic torque during the three phases are shown in Table IV. Analysis of variance showed highlighted differences between the components for all comparisons. A significant interaction between stroke style and the components of the right hip joint during the late backswing phase was also observed. Using post-hoc tests, significant differences in mean values were found for some combinations of the components at each hip joint. In short, the adduction moment at the right hip joint during the late backswing phase was a large contributor in both strokes. (Table IV shows these differences in detail.)

Examples of the contributions of the anatomical components of the hip joint moment to pelvic torque are shown in Figure 7. The general patterns of the curves in the two-handed stroke were similar to those in the one-handed stroke. At the right hip joint, all participants showed a large adduction moment (Figure 7b,d). The peak of the contribution curve due to the adduction moment was recorded at the beginning of the forward swing phase. The extension moment at the left hip joint showed a large positive contribution (Figure 7a,c). Note that the adduction moment at the right hip joint showed a large contribution in the one-handed stroke, while the extension moment at the left hip joint showed a large contribution in the two-handed stroke (Figure 7b,c).

**Discussion**

The results of the present study should be interpreted with caution because of possible errors from an inverse dynamic approach when applied to analyses of human movements. It is known that several errors might influence the joint moment determined using inverse dynamics. In their study of walking, Cappozzo, Leo and Pedotti (1975) reported major errors in determining the positions of body segments with respect to the vectors of ground reaction forces. Artefacts due to skin movements are also the source of error (Cappozzo, Catani, Leardini, Benedetti, & Della Croce, 1996; Manal, McClay, Davis, Galinat, & Stanhope, 2003).

Iino and Kojima (2001) assessed the effect of the accuracy of the positions of the hip joint centre and the centre of pressure of the foot on the estimated hip joint moment and pelvic torque in the tennis forehand. They reported that the general profiles of the joint moment and the pelvic torque were not substantially affected by the accuracies in the system they used for experimentation and data processing. A system similar to that used by Iino and Kojima (2001) was used in the present study. Hence, the
accuracies in terms of the location of the hip joint centres and the centre of the pressure in the present study should be similar those reported by Iino and Kojima (2001).

The errors in estimating the locations of the hip joint centres would be the most important source of error in the present study. Leardini et al. (1999) reported that the method of Bell et al. (1990) used in the present study estimated the location of the hip joint centre 7.2 mm posterior, 18.7 mm below and 5.3 mm lateral to the true location. Based on the results of Leardini et al. (1999), the adduction and extension hip joint moments calculated in our study may have been underestimated and the abduction and flexion moments may have been overestimated.

Cappozzo et al. (1996) studied the artefact of the skin movements of the leg during walking and cycling tasks and found that the size of the artefact was closely related to the angular displacement of the relevant joint irrespective of the movements used.

Both the error of the regression method of Bell et al. (1990) in estimating the locations of hip joint centres and the errors due to skin movement artefacts of the legs have systematic errors in themselves (Cappozzo et al., 1996; Leardini et al., 1999). Much of the leg kinematics of the one-handed stroke is similar to that in the two-handed stroke: the difference in minimum angle of the right and left knee joints between the strokes was 1.2° and 4.4°, respectively, and the difference in the range of angular displacement of the right and left knee joints between the strokes was 4.3° and 5.0°, respectively. Hence, we believe that much of the systematic error would be removed in the results regarding the differences between the two types of stroke.

Special care was taken to enable each participant to hit a ball with “good technique”. The mean racket head speeds of 18.8 and 18.9 m·s⁻¹ just before ball impact in the one-handed and the two-handed strokes, respectively, were almost identical to the speed of 18.9 m·s⁻¹ in the one-handed on-court backhand strokes in the study by Elliott et al. (1989). Thus, the strokes in the present study appear to have been performed without much constraint.

Scheffe’s tests instead of Tukey’s tests were used to identify differences in the integrated contributory components and the integrated contributions of the anatomical components of the hip joint moment to pelvic torque between the two types of stroke (Tables III and IV). Scheffe’s tests were used because we hypothesized that some but not all comparisons of the means of two components would be meaningful between the two types of stroke (Toothaker, 1993).

Scheffe’s tests for rejection were performed, Table III. Mean integrated contributions of the components of pelvic torque during the three phases (N·m·s⁻¹·kg⁻¹)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Component</th>
<th>Left Joint Moment</th>
<th>Right Joint Moment</th>
<th>Left Joint Force</th>
<th>Right Joint Force</th>
<th>Pelvic Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Backswing Phase</td>
<td>One-handed (mean±s)</td>
<td>0.006±0.007</td>
<td>0.000±0.009</td>
<td>-0.003±0.008</td>
<td>0.003±0.004</td>
<td>0.007±0.009</td>
</tr>
<tr>
<td></td>
<td>Two-handed (mean±s)</td>
<td>0.014±0.013</td>
<td>0.005±0.014</td>
<td>-0.001±0.005</td>
<td>0.002±0.004</td>
<td>0.021±0.027</td>
</tr>
<tr>
<td>Late Backswing Phase</td>
<td>One-handed (mean±s)</td>
<td>0.011±0.018</td>
<td>0.026±0.009</td>
<td>-0.004±0.012</td>
<td>0.012±0.009</td>
<td>0.044±0.022</td>
</tr>
<tr>
<td></td>
<td>Two-handed (mean±s)</td>
<td>0.031±0.009</td>
<td>0.006±0.007</td>
<td>0.001±0.005</td>
<td>0.011±0.005</td>
<td>0.050±0.009</td>
</tr>
<tr>
<td>Forwardswing Phase</td>
<td>One-handed (mean±s)</td>
<td>0.009±0.012</td>
<td>0.004±0.015</td>
<td>0.003±0.003</td>
<td>0.015±0.008</td>
<td>0.031±0.016</td>
</tr>
<tr>
<td></td>
<td>Two-handed (mean±s)</td>
<td>0.013±0.010</td>
<td>-0.004±0.017</td>
<td>0.001±0.002</td>
<td>0.016±0.010</td>
<td>0.027±0.020</td>
</tr>
</tbody>
</table>

Note: The lines connecting two values means that there was a significant difference between those values. The bold lines indicate differences according to Tukey’s multiple comparison tests and the thin lines indicate differences according to Scheffe’s multiple comparison tests. Mean values after excluding the data of one unrepresentative “one-handed” participant are shown in parentheses. Dashed lines indicate differences according to comparison tests after the exclusion.
which confirmed that the results for this “one-handed” participant could be rejected. The reasons why this participant was able to generate such large moments are unknown.

The statistical differences in the swing time, normalized times of the swing, all kinematic data and most of the kinetic data between the two styles of stroke did not change after excluding the results of this “one-handed” participant. The mean contributions of the anatomical components of the hip joint to pelvic torque after the exclusion were as follows: left extension moment $0.023 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$, left abduction moment $0.010 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$, left external rotation moment $-0.016 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$. The extension moment showed a large contribution to pelvic torque in the left hip joint (Table IV).

**General aspects of the tennis backhand stroke**

The patterns of the curves of the anatomical components of the hip joint moment to pelvic torque after the exclusion were as follows: left extension moment $0.023 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$, left abduction moment $0.010 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$, left external rotation moment $-0.016 \text{ N} \cdot \text{m} \cdot \text{s} \cdot \text{kg}^{-1}$. The extension moment showed a large contribution to pelvic torque in the left hip joint (Table IV).

**Differences in stroke styles**

There was no statistical difference in swing time between the one-handed and two-handed strokes. The normalized times of the completion of the backward rotation of the pelvis, the completion of the backward rotation of the racket, and the occurrence of peak pelvic torque were not significantly different between the strokes. The range of pelvic angular displacement and the angular velocity of the pelvis from the beginning of the late backswing phase to ball impact were significantly larger in the two-handed stroke than in the one-handed stroke (Table II). These results indicate that the timing of motion of the two-handed stroke was similar to that of the one-handed stroke (Table I), while the pelvis rotated.

<table>
<thead>
<tr>
<th>Early Backswing Phase</th>
<th>Left Hip Joint</th>
<th>Right Hip Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-handed (mean±s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension (+)</td>
<td>0.004±0.004</td>
<td>-0.003±0.004</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>0.004±0.005</td>
<td>-0.003±0.005</td>
</tr>
<tr>
<td>External Rotation (+)</td>
<td>-0.002±0.002</td>
<td>-0.002±0.002</td>
</tr>
<tr>
<td>Two-handed (mean±s)</td>
<td>0.011±0.009</td>
<td>0.018±0.015</td>
</tr>
<tr>
<td>Extension (+)</td>
<td>0.001±0.007</td>
<td>-0.004±0.011</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>-0.006±0.008</td>
<td>-0.009±0.009</td>
</tr>
<tr>
<td>External Rotation (+)</td>
<td>-0.003±0.010</td>
<td>-0.003±0.010</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Late Backswing Phase</th>
<th>Left Hip Joint</th>
<th>Right Hip Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-handed (mean±s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension (+)</td>
<td>0.016±0.018</td>
<td>0.027±0.049</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>0.002±0.009</td>
<td>-0.033±0.048</td>
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<tr>
<td>External Rotation (+)</td>
<td>0.014±0.009</td>
<td>-0.001±0.007</td>
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<tr>
<td>Two-handed (mean±s)</td>
<td>0.030±0.012</td>
<td>0.007±0.012</td>
</tr>
<tr>
<td>Extension (+)</td>
<td>-0.002±0.004</td>
<td>-0.016±0.010</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>-0.006±0.008</td>
<td>-0.008±0.009</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forwardswing Phase</th>
<th>Left Hip Joint</th>
<th>Right Hip Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-handed (mean±s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension (+)</td>
<td>0.014±0.017</td>
<td>-0.007±0.016</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>0.002±0.011</td>
<td>-0.003±0.010</td>
</tr>
<tr>
<td>External Rotation (+)</td>
<td>-0.004±0.005</td>
<td>-0.004±0.005</td>
</tr>
<tr>
<td>Two-handed (mean±s)</td>
<td>0.012±0.010</td>
<td>0.000±0.005</td>
</tr>
<tr>
<td>Extension (+)</td>
<td>0.004±0.004</td>
<td>-0.003±0.010</td>
</tr>
<tr>
<td>Abduction (+)</td>
<td>0.004±0.003</td>
<td>0.000±0.005</td>
</tr>
</tbody>
</table>

Note: Lines connecting two values mean that there was a significant difference between those values. Mean values after excluding the data of one unrepresentative “one-handed” participant are shown in parentheses. Dashed lines indicate differences after the exclusion was made.
further forward and more quickly during the late backswing phase and the forward swing phase in the two-handed stroke than in the one-handed stroke (Table II).

The range of pelvic angular displacement from the beginning of the late backswing phase to the point of impact in the two-handed stroke (54.4°) was greater than that in the one-handed one (31.4°) even though the pelvis rotated forward from almost the same angular position in both strokes (Table II). Consequently, in terms of pelvic rotation defined by the pelvic angle, “two-handed” players hit the ball in a more “open” position (153.2°) than the “one-handed” players (170.2°). This is in line with the results of Reid and Elliott (2002). The reason for the difference between the two strokes might relate to differences in upper body motion between the strokes. Forward rotation of the trunk to take the racket to the impact point could not be achieved without a large pelvic rotation in the two-handed stroke because of the restriction on shoulder movement by the left arm. Hence, a larger pelvic rotation observed in the two-handed stroke might be needed to hit the ball under such upper body restriction.

Reid and Elliott (2002) reported that the angular displacement of the pelvis at the end of the backswing in the one-handed backhand stroke was significantly larger than in the two-handed backhand
stroke. In the present study, there was no difference in angular displacement of the pelvis at the end of the backswing between the two strokes. The reason for the difference between the two studies could be explained by the difference in time when this event was measured: the pelvis might have started to rotate forward before the completion of the backswing in the study of Reid and Elliott (2002).

It has been reported that the impact position in the one-handed stroke is significantly further from the direction in which the ball is hit than in the two-handed stroke (Groppel, 1992; Reid and Elliott, 2002). In spite of these results, the positions of the two types of stroke in the present study were similar (one-handed, 0.044 m; two-handed, 0.044 m). The reason for this inconsistency was unclear.

As discussed on p. 790, the extension moment at the left hip joint and the adduction moment at the right hip joint during the late backswing phase were important for pelvic torque in the one-handed stroke and two-handed stroke, respectively (Table IV). Regarding the components of pelvic torque, the right hip joint moment in the one-handed stroke provided a larger contribution than that in the two-handed stroke (Table III). In contrast, the contribution of the left hip joint moment in the two-handed stroke was larger than in the one-handed stroke (Table III). Thus, the adduction moment at the right hip joint and the extension moment at the left hip joint during the late backswing phase are important for pelvic rotation in the one-handed and two-handed strokes, respectively. However, the reasons for the difference between the strokes are unclear.

Comparison of backhand stroke with forehand stroke in tennis

The angular displacement of 54.4° of the pelvis during its forward rotation in the two-handed backhand stroke was larger than the displacement of 31.4° in the one-handed backhand stroke (Table II), and comparable to the displacement of 60.3° in the forearm ground stroke (Iino and Kojima, 2001).

That the hip joint moment of the back leg (the hip extension moment in particular) showed a large contribution to pelvic torque in the two-handed backhand ground stroke is comparable to the finding that the same moment showed the largest contribution to pelvic torque in the forearm ground stroke (Iino and Kojima, 2001). Thus, the roles of the lower extremities in trunk rotation in the two-handed backhand ground stroke were similar to those of the lower extremities in the forearm stroke in tennis. However, the roles of the lower extremities in the one-handed backhand stroke were different from the roles of the lower extremities in the forearm stroke in tennis. In terms of the hip joint moments for pelvic rotation, the results of the present study support the observation of Yandell (1998) that the biomechanics of the two-handed stroke are similar to those used to hit a forehand on the opposite side.

In conclusion, we found that the joint moment of hip adduction at the right or front leg was dominant over forward rotation of the pelvis in the one-handed backhand stroke while the joint moment of hip extension at the left or back leg was dominant over the rotation in the two-handed backhand stroke. This suggests that there are some differences in roles of the lower extremities in generating the pelvic rotation between the one-handed and two-handed backhand strokes and that the roles in the two-handed backhand stroke were similar to those in the forearm ground stroke.

References


Trunk rotation torques in the backhand tennis stroke


