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Research article

Pelvic Rotation and Lower Extremity Motion with Two Different Front Foot Directions in the Tennis Backhand Groundstroke

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Abstract
When a tennis player steps forward to hit a backhand groundstroke in closed stance, modifying the direction of the front foot relative to the net may reduce the risk of ankle injury and increase performance. This study evaluated the relationship between pelvic rotation and lower extremity movement during the backhand groundstroke when players stepped with toes parallel to the net (Level) or with toes pointed towards the net (Net). High school competitive tennis players (eleven males and seven females, 16.8 ± 0.8 years, all right-handed) performed tennis court tests comprising five maximum speed directional runs to the court intersection line to hit an imaginary ball with forehand or backhand swings. The final backhand groundstroke for each player at the backcourt baseline was analyzed. Pelvic rotation and lower extremity motion were quantified using 3D video analysis from frontal and sagittal plane camera views reconstructed to 3D using DLT methods. Plantar flexion of ankle and supination of the front foot were displayed for both Net and Level groups during the late phase of the front foot step. The timings of the peak pelvis rotational velocity and peak pelvis rotational acceleration showed different pattern for Net and Level groups. The peak timing of the pelvis rotational velocity of the Level group occurred during the late phase of the step, suggesting an increase in the risk of inversion ankle sprain and a decrease in stroke power compared to the Net group.

Key words: Ankle, sprains, prevention, lower extremity movements, pelvic rotational velocity, pelvic rotational acceleration.

Introduction

Tennis is a globally popular sport enjoyed by many, regardless of age or level (ITF, 2013). However, there are a reported 2.5 injuries/player (male), 2.9 injuries/player (female) (Reece et al., 1986), and 3.0 injuries/1000 h (Jayanthi et al., 2005). According to epidemiological survey results by Iwamoto (2011) and Hutchinson (1995), the most frequent acute injury is ankle sprain (44.7% – 58.0%) (Iwamoto et al., 2011, Hutchinson et al., 1995).

Injury prevention strategies are based on an understanding of causative factors or the mechanisms of injury (van Mechelen et al., 1992). Although biomechanical research has investigated tennis injuries to the upper extremities and the mechanisms of overuse injuries – in particular, injuries to the shoulder joint (van der Hoeven and Kibler, 2006) and elbow joint (Loftice et al., 2004) limited research has been conducted on the biomechanics of inversion ankle sprains in tennis.

Inversion ankle sprains in tennis are usually caused by sudden stopping or changes of direction (Babette and Marc, 2004), and frequently arise during backhand groundstrokes (BHGS) (Weijermans et al., 1998). For BHGS, adopting a front stepping foot position, where the toes are oriented toward the net, may reduce ankle inversion risk (Babette and Frank, 2003). When players perform BHGS with their front stepping foot parallel to the net, rotational torque at the ankle is increased because the foot becomes a pivot point for the gradual rotation of their pelvis, trunk, and shoulders. However, there have been no biomechanics studies investigating the relationship of inversion ankle sprains and front foot position during backhand strokes. Thus, the context in which inversion ankle sprains occur during BHGS is not clearly understood.

This study aimed to determine the relationship between pelvic rotation and lower extremity movement during BHGS when players stepped with their toes parallel to the net (Level) or with their toes pointed towards the net (Net). In addition, the study sought to determine whether it was theoretically possible to reduce the risk of ankle inversion sprains by orienting the toes of the front foot towards the net.

Methods

The Ethics Committee of the Faculty of Human Life Design at Toyo University approved the experimental procedure of this study. Written informed consent was gained from all participants and their guardians before the experiment.

Participants

Participants included eighteen right-handed tennis players – eleven male (age: 17.3 ± 0.7 years, weight: 61.8 ± 8.0 kg, height: 1.71 ± 0.7 m) and seven female (age: 16.7 ± 0.5 years, weight: 53.0 ± 5.5 kg, height: 1.55 ± 0.05 m). All were tennis players at the highest level of high school competition.

Experimental procedures

The players wore sleeveless shirts, shorts, and their own tennis shoes. Joint, racquet and shoes markers were attached to 33 points as outlined in Figure 1. After warming up (jogging, dynamic stretching, and two sub-max speed five directional runs with swing), each player performed five directional runs (Michikami, 2004) while swinging their racket to hit an imaginary ball on a tennis hard court

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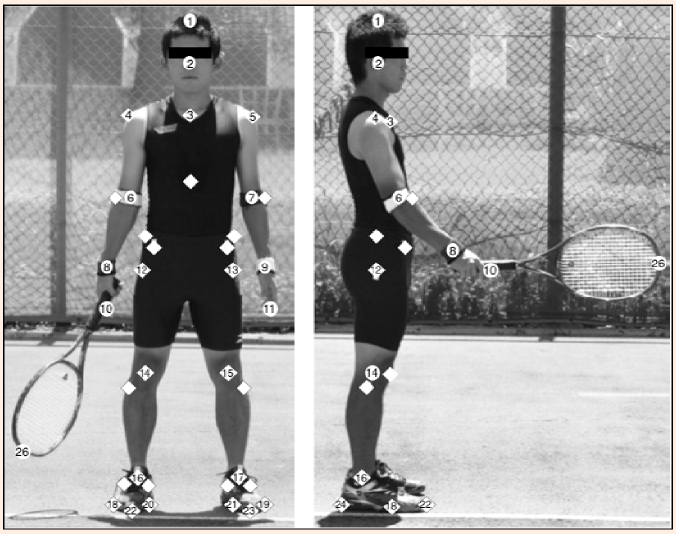

Figure 1. Locations of body markers and digitized points on study participants. Twenty-six digitized points were used in this study – 17 points according to the protocol of Ae (1996) and nine tennis-specific points. Their locations were as follows: top of the head (1), center point between the ears (2), episternum (3), most lateral acromion on the right (4) and left (5) sides, center of the right (6) and left (7) elbow joints, center of the right (8) and left (9) wrist joints, tips of the fingers on the right (10) and left (11) hands, most lateral aspect of the greater trochanter on the right (12) and left (13) sides, center of the right (14) and left (15) knee joints, center of the right (16) and left (17) ankle joints, most lateral point on the bottom of the right (18) and left (19) shoe, most medial point on the bottom of the right (20) and left (21) shoe, most frontal point on the bottom of the right (22) and left (23) shoe, most posterior point on the bottom of the right (24) and left (25) shoe, and most distal point on the tennis racket (26).

(Figure 2). These movements included running, stopping, and changing direction with maximum speed and swinging. The players completed five directional runs BHGS were performed double-handed with a closed stance. The swing was at hip-level and the aim was crosscourt at the baseline.

The criterion for dividing players into the "Net" and "Level" groups was the position of the players' front stepping foot relative to the net during the contact phase of the backhand groundstroke. Thirty-seven subjects performed a backhand groundstroke, and their front stepping foot contact phase (FSFCP) angles were measured using video data. The nine players whose FSFCP angle was the highest were assigned to the "Net" group, and the nine players whose FSFCP angle was the lowest were assigned to the "Level" group. The mean angle for the "Net" group was 30.6 ± 7.2°. The mean angle for the "Level" group was 0.0 ± 10.0°. Players were videoed from the frontal plane and sagittal plane with digital video cameras sampling at 60 Hz (NV-GS250, Panasonic, Japan). The data was synchronized before analyses (Figure 1).

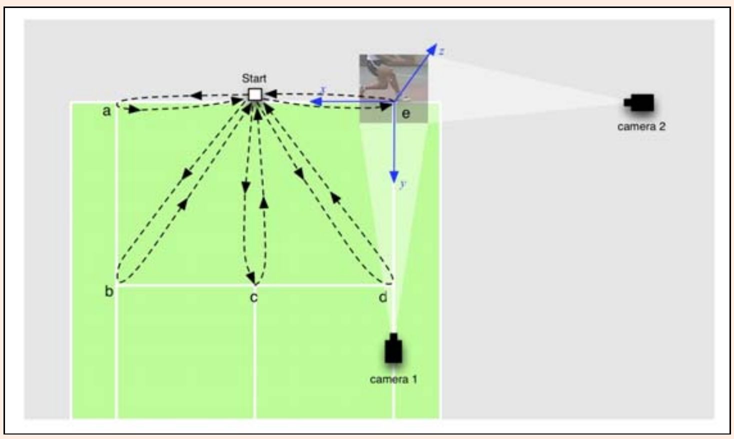

Figure 2. Tennis test and experimental set-up. Each participant completed five directional runs while swinging and "hitting" an imaginary ball at the following points: the intersection between the forecourt baseline and the forecourt singles side line with a forehand groundstroke (a); the intersection between the forecourt service line and the forecourt singles side line with a forehand volley (b); the intersection between the service line and the centerline with a touch of the racquet on the court (c); the intersection between the backcourt service line and the backcourt singles side line with a backhand volley (d); and the intersection between the backcourt baseline and the backcourt singles side line with a backhand groundstroke (e). At the end of each run, the participant returned to the start box (30 cm × 30 cm), located on the center of the base line. Two video cameras were setup for continuous video recording and were focused on the backhand groundstroke at position e.

Analyses

Using data from the FSFCP, positions of the landmarks were manually digitized using a motion analyzer (Frame-DIAS, DKH, Japan) and then three dimensional coordinates were calculated using a direct linear transformation (DLT) method (Abdel-Aziz and Karara, 1971). Digitized data were low-pass filtered at 6 Hz with a bidirectional Butterworth filter (Winter, 1990).

Coordinates of the markers and joints centers

The field of videoing was 3.0 m × 3.0 m into the center points of intersection between the baseline and backcourt singles sideline, and height was two meters. In order to determine DLT coefficients for each camera and to calibrate the video before data collection, eighty markers were placed within a 3.0 m × 3.0 m × 2.0 m cubic matrix. This study used the global axis with markers spaced at 1 m intervals on the X-axis (parallel to the baseline), at 1 m intervals on Y-axis (perpendicular to the baseline), and at 0.5 m intervals on the Z-axis (vertical axis).

Estimation of the lower extremity movements

The foot angle (Foot) was defined as the angle between surface of the tennis court and a line connecting the heel to the toe (sagittal plane). Foot was negative when the heel was higher than the toe. The leg angle (Leg) was defined as the angle between the surface of the tennis court and a line connecting the ankle to the knee (sagittal plane). Leg was toe from the right horizontal. The forefoot eversion/inversion angle (Forefoot) was defined as the angle between the surface of the tennis court and a line connecting the small toe to the big toe (frontal plane). Forefoot was negative when the forefoot was in a supination position. In addition, the ankle angle (Ankle) was calculated as follows:

$$\text{Ankle} = \text{Leg} - \text{Foot}$$

When Ankle was larger than 90°, the ankle was in a planter flexed position.

Estimation of the pelvis rotation

In this study, the pelvis rotation motion was defined as the angular motion between a line connecting the left and right greater trochanter points and the X-axis (horizontal plane). The angular velocity (ω) and angular acceleration (α) of the pelvis rotation was calculated using the following equations:

$$\text{Angle } \phi = \mathrm{a}\cos\left(\frac{L_x}{|L|}\right)$$

$$\omega = \frac{d}{dt}\phi$$

$$\omega = \frac{-\varphi_{t-1} + \varphi_{t+1}}{2\Delta t}$$

$$\alpha = \frac{d}{dt}\omega$$

$$\alpha = \frac{-\omega_{t-1} + \omega_{t+1}}{2\Delta t}$$

where L was the length of the line between the left and right greater trochanter points, ϕ was the angle between that line and the X-axis, and t was time (s).

The positive angular movement was in the clockwise direction.

Normalization

The duration of the analyses was normalized for each participant from 0% at the moment the foot first contacted the court to 100% when the foot took off completely from the court. In this study, the impact timing was defined as the moment when the racket was parallel to the baseline. All players had the impact timing during the FSFCP.

Statistical analysis

Values for rotational velocity of the pelvis, acceleration of the pelvis rotation, Foot, Forefoot, Leg, and Ankle were sampled for each 5% interval during the normalized duration of analysis. Mean and standard deviations were then calculated and compared for the Level (n = 9) and Net (n = 9) groups. This study used a two-way analysis of variance (ANOVA) with repeated measures for comparisons were performed between Level and Net groups at each sampled 5% interval by the Bonferroni test. The level of significance was at 5%.

Results

How lower extremity movements are influenced by the direction of the front stepping foot

Figure 3 shows Leg and Ankle data (Figure 3A), as well as Foot and Forefoot data (Figure 3B) for the front stepping foot averaged for all players in both Level and Net groups during the FSFCP. For Leg, the ANOVA showed the interaction effect between group and percentage of FSFCP was significant. The post-hoc Bonferroni tests indicated 1% to 10% of FSFCP. Leg values for Net were larger than those for Level during the early phase of FSFCP. The greatest difference was at 1% FSFCP (Net: 121 ± 7°, Level: 102 ± 7°) ($p = 0.031$). During the first half of FSFCP, Leg values for both Net and Level gradually decreased, then during the second half, values for Net were mostly unchanged and those for Level slightly increased (Figure 3A).

For Forefoot, the ANOVA showed the interaction effect between group and percentage of FSFCP was also significant. The post-hoc Bonferroni tests indicated 1% to 5% and 25% to 80% of FSFCP. Forefoot values changed significantly for the Net group compared to the Level group. The greatest difference was at 75% FSFCP (Net: 0.0 ± 4.2°, Level: -8.0 ± 4.4°) ($p = 0.001$). For both Level and Net groups, Forefoot values increased during the early phase of FSFCP, leveled off during the middle phase, and then decreased during the late phase. However, values for the Level group changed less than the Net group and were always negative. This means that the forefoot was in a supinated position for the duration of FSFCP (Figure 3B). Ankle and Foot values were not influenced by the direction of the front stepping foot during FSFCP for both Net and Level groups. Ankle values for both Level and Net increased until approximately 25% FSFCP, then gradually decreased to 100° (Figure 3A).

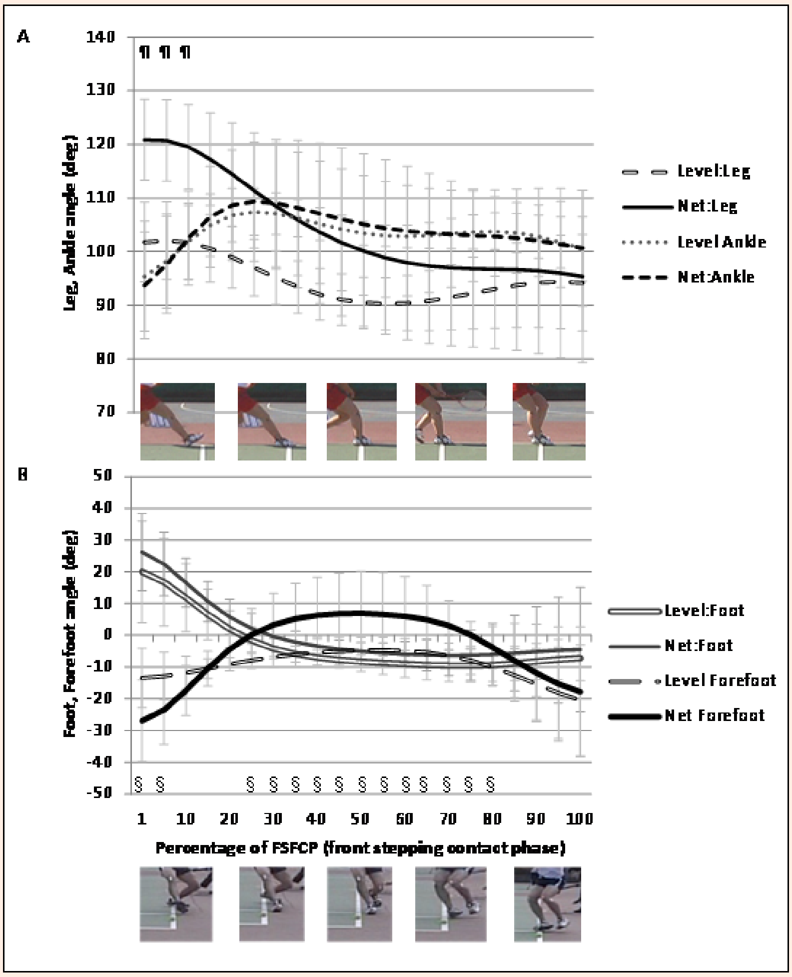

Figure 3. The change of Leg, Ankle angles (A) and the change of Foot, Forefoot (B) during the FSFCP normalized to 100%. ¶ Significant difference at Leg ($p < 0.05$). § Significant difference at Forefoot ($p < 0.05$).

Foot values for both Level and Net groups were initially positive, and became negative at approximately 25% FSFCP. Positive values for Foot occurred when the heel was lower than the toe, meaning that the first contact to the court was the heel for both Level and Net groups. Negative values for Foot occurred when the heel was higher than the toe, meaning that the heel was raised and only the forefoot was in contact with the court after 25% FSFCP (Figure 3B).

How pelvis rotation is influenced by the direction of the front stepping foot

Figure 4 shows the mean values for the rotational velocity of the pelvis (Figure 4A) and the acceleration of the pelvis rotation (Figure 4B) for Level and Net groups. The thick horizontal arrows indicate that the timing of impact for participants in the Level group ranged from 41% to 75% of FSFCP (red arrow), and for participants in the Net group ranged from 47% to 79% of FSFCP (green arrow). The thin horizontal arrows indicate that the timing of maximum rotational velocity of the pelvis for players in the Level group ranged from 68% to 99% of FSFCP, and for participants in the Net group ranged from 20% to 66% of FSFCP.

For rotational velocity of pelvis, the ANOVA showed the interaction effect between group and percentage of FSFCP was significant. The results of the post-hoc Bonferroni tests indicated 15% to 45% and 75% to 100% of FSFCP. The maximum rotational velocity of the pelvis for the Net group was in the first half of FSFCP before impact (Figure 4A). However, maximum rotational velocity of pelvis for the Level group was in the second half of FSFCP after impact. The greatest difference in rotational velocity of the pelvis for the two groups was at 85% FSFCP (Net: 209 ± 43 °/s, Level: 351 ± 82°/s) ($p = 0.000$) (Figure 4A).

For acceleration of pelvis rotation, the ANOVA showed the interaction effect between group and percentage of FSFCP was significant. The results of the post-hoc Bonferroni tests indicated 15% to 20% and 50% to 75% of FSFCP. The maximum acceleration of the pelvis rotation for the Net group was in the first half of FSFCP before impact (Figure 4B). However, maximum acceleration of the pelvis rotation for the Level group was in the second half of FSFCP during impact. The greatest difference in acceleration of the pelvis rotation for the two groups was at 60% FSFCP (Net: -282 ± 1893°/s^2, Level: 2067 ± 1110 °/s^2) ($p = 0.005$) (Figure 4B).

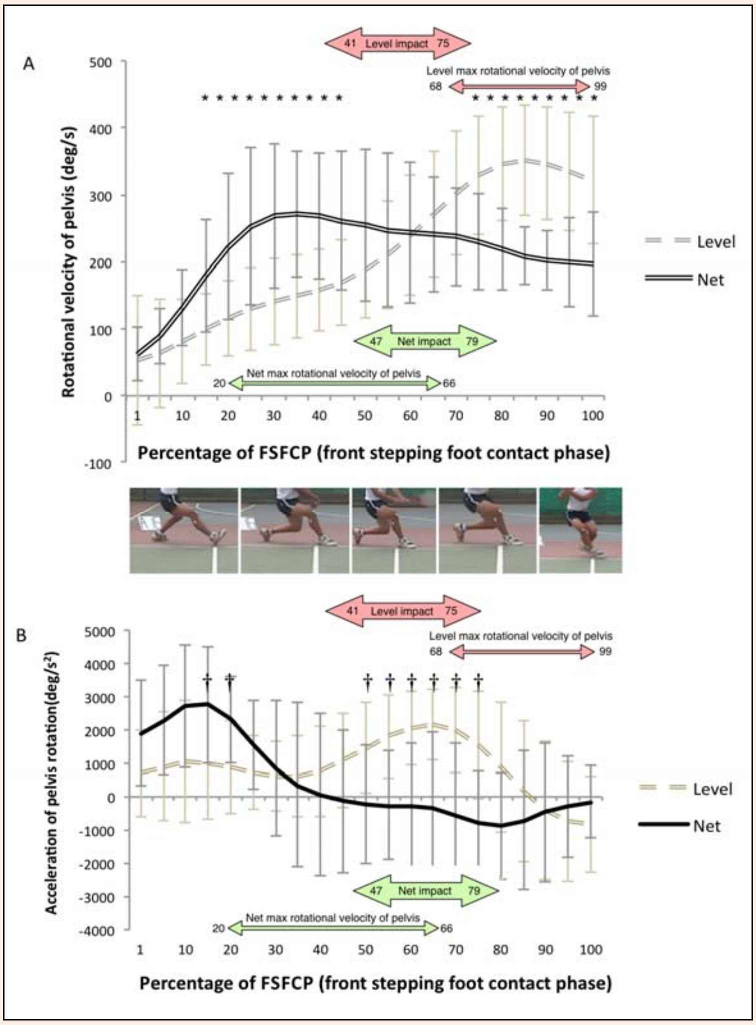

Figure 4. The change in the rotational velocity of the pelvis (A) and the acceleration of the pelvis rotation (B) during the FSFCP normalized to 100%. The thick arrows indicate the range of impact timing for each participant with black representing the Level group and white representing the Net group. The thin arrows indicate the range of max velocity timing for each subject. * Significant difference at rotation velocity ($p < 0.05$). † Significant difference at acceleration of pelvis rotation ($p < 0.05$).

Discussion

Backhand groundstrokes (BHGS) accompanied with running and stopping involves translational and rotational motion. The pelvis and upper extremities must move during FSFCP as part of the swinging motion needed for impact and post-impact follow-through while stepping forward. In addition this phase involves a dramatic deceleration of linear movement with an acceleration of angular motion (Iwamoto, 2011). These movements have implications for both the risk of injury and performance in tennis; however, there has been limited research that has attempted to study how these movements occur during tennis.

The direction of the front stepping foot in BHGS may influence the risk of inversion ankle sprain. According to the results, after approximately 25% FSFCP for both Level and Net groups, the foot angle was negative (i.e., the heel was higher than the toe) and the leg angle was greater than 90° (i.e., the leg is extended in front), which means that the ankle was in planter flexion. As for the movement of the forefoot, the Net group showed a pattern of supination-pronation-supination during FSFCP. However, the Level group showed only supination of various degrees during FSFCP.

Vitale and Fallatt (1988) and Fong et al. (2007) stated that plantar flexion and supination were the injury mechanisms of inversion ankle sprain. With respect to lower extremity movements, the results of this study showed that there was potentially a high risk of inversion ankle sprain for the Net group in the late phase of FSFCP, and for the Level group after 25% FSFCP.

In terms of maximum angular velocity of pelvis rotation, the values for the Level and Net groups were different. For the Net group, the maximum angular velocity occurred in the early phase of FSFCP before impact. For the Level group, however, the maximum angular velocity occurred in the latter phase of FSFCP after impact, which, together with the lower extremity movements of plantar flexion and supination, put Level group players at a potentially higher risk of inversion ankle sprain during BHGS. This increased potentially risk was due to the fact that participants ran, suddenly decelerated while stepping with their front foot in plantar flexion and supination, and then performed a high-speed rotational motion.

Fong et al. (2007) explained that excess plantar flexion and the degree of supination at the point of sudden deceleration could increase the risk of inversion ankle sprain (Fong, et al, 2007. Vitale and Fallatt, 1988). The results of this study support the suggestion of Babette and Fran (2003) that having the foot oriented towards the net during the backhand ground stroke may potentially helps prevent an inversion ankle sprain.

This study also has interesting implications for tennis performance. The power of a tennis stroke is transmitted from the lower extremities through the trunk, upper extremities, hands, and racquet (Akutagawa and Kojima, 2005; Iino and Kojima, 2001; 2003). This kinetic chain is very important for the effective transfer of force to the ball (Nesbit et al, 2008). Wang reported that backhand stroke angular motion and stroke power was greater in advanced players due to their use of efficient kinetic chains (Wang et al., 2010). However, there was no evidence that foot orientation affects upper body movement in any particular way (Iwamoto, 2011).

In spite of individual variations, the impact with the imaginary ball occurred at the middle phase of FSFCP for both Level and Net groups. However, the maximum rotational velocity of the pelvis occurred before impact for the Net group and after impact for the Level group. This implies that the Level group transferred less force to the imaginary ball because the kinetic chain transmission was not as effective. Therefore, the toe orientation of the Net group may be regarded as technically more effective for the efficient transfer of force if players seek a more powerful shot. If players who are classified as “Net” use a “Level” orientation, they may incur a potentially greater risk of inversion ankle sprain during the backhand groundstroke. In terms of performance, changing from “Net” to “Level” may decrease the power of the shot.

This study used a series of movements to simulate real tennis movement on a hard court. However, the study has some limitations. Firstly, only two cameras were used to record the three-dimensional movement. While this was sufficient for the purposes of the study, greater data accuracy could have been obtained through the use of three or more cameras. Secondly, data were collected at 60 Hz, which is a relatively low frequency for tennis research. However, since this study focused on lower body movement, which is relatively slower compared to upper body movement, this frequency was adequate. Thirdly, the global axis was used, which makes it difficult to describe internal body angles, such as ankle angle. Usually in discussions of injuries, researchers refer to joint angles. However, for lower extremity injuries in tennis, the relationship between foot-load and the ground surface is important (Girard, 2007).

In summary, orienting the front stepping foot in the direction of the net while executing Backhand groundstrokes reduces the risk of inversion ankle sprains and results in a more effective kinetic chain, which ultimately enhances performance.

Conclusion

The orientation of the front stepping foot – toes pointing towards the net or parallel to the net – during Backhand groundstrokes resulted in different patterns in the rotation of the pelvis. The risk of inversion ankle sprains during Backhand groundstrokes was largely influenced by two factors: the position of the front stepping foot relative to the ground surface and the timing of maximum angular velocity of the pelvis. Based on these factors, the Level group showed a greater potential risk of inversion ankle sprain as compared to the Net group.

To enhance the performance of Backhand groundstrokes, an effective kinetic chain must be used. This study found that orienting the front stepping foot in the direction of the net led to a properly sequenced kinetic chain, which suggests potentially better power transfer and enhanced performance.

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Key points

- Regarding the movement of the forefoot, the Net group and the Level group showed a pattern of supination-pronation-supination during the front stepping foot contact phase (FSFCP). However, the Level group showed only supination of various degrees during FSFCP.
- For the Net group, the maximum angular velocity of pelvis occurred in the early phase of FSFCP before impact; however, for the Level group, the maximum angular velocity of pelvis occurred in the latter phase of FSFCP after impact.
- The Level group players showed a potentially higher risk of inversion ankle sprain during the latter stage of FSFCP as pelvic rotation reached maximum angular velocity.
- The Net group may have a more effective kinetic chain during backhand groundstrokes, which ultimately enhances performance.

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