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Research article

Kinematic Comparisons of the Shakehand and Penhold Grips in Table Tennis Forehand and Backhand Strokes when Returning Topspin and Backspin Balls

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Abstract

Identifying the factors associated with table tennis performance may provide training information for competitive athletes and guide the general population for active participation. The purpose was to compare the joint, racket, and ball kinematics between the shakehand and penhold grips in table tennis forehand and backhand strokes when returning topspin and backspin balls in advanced male players. Nine penhold-grip players and 18 matched shakehand-grip players performed forehand and backhand strokes when returning topspin and backspin balls using their habitual grip styles, while the kinematics of the trunk, upper extremities, racket, and ball were collected. Racket angles were calculated as the relative motion of the racket to the forearm. For the forehand strokes, no significant differences were observed for ball or racket velocities between the two grips. The shakehand grip tended to demonstrate greater shoulder external rotation angles compared to the penhold grip. The shakehand grip resulted in racket *flexion* angular velocity compared to racket *extension* velocity for the penhold grip. For the backhand strokes, greater ball and racket velocities were observed for the shakehand grip. The shakehand grip generally demonstrated decreased final trunk left rotation angles, increased trunk right rotation angular velocities, decreased final shoulder abduction angles, increased shoulder adduction angular velocities, and increased forearm supination angular velocities. The two grips demonstrated similar peak racket and ball velocities but different shoulder rotation range of motion and racket motion in forehand strokes. The penhold grips resulted in decreased peak racket and ball velocities in backhand strokes, likely due to its decreased shoulder, elbow, and forearm motion and less aligned longitudinal axes between the racket and forearm. These findings may help understand the dominance of the shakehand grip over the penhold grip in elite athletes and provide information for grip selection, technique improvements, and exercise training.

Key words: Ping-pong, biomechanics, motion, performance, techniques.

Introduction

Table tennis is a popular sport contested at the Summer Olympic Games. The 2016 Rio Olympic Games attracted more than 500 million TV viewers from over 170 countries (International Table Tennis Federation, 2019). Table tennis is also a common recreational activity, with 21% of the global population having an interest (International Table Tennis Federation, 2019). Participation in recreational table tennis was associated with better physical performance, improved body composition, as well as increased muscle strength in male older adults (Naderi et al., 2018). Because of the health benefits and training flexibilities associated with table tennis, it has been recommended as an effective tool to increase leisure-time physical activities (Biernat et al., 2018). Identifying the factors to improve table tennis performance may provide training information for competitive athletes and guide the general population for active participation.

Kinematic analyses have been utilized to compare table tennis forehand and backhand strokes and athletes with different performance levels to identify critical techniques. The forehand strokes mainly utilize the motion of trunk axial rotation, shoulder flexion, and shoulder internal rotation to produce racket linear velocities (Iino and Kojima, 2009). The backhand strokes primarily involve shoulder external rotation and flexion, elbow extension, forearm supination, and wrist extension (Iino et al., 2008). In addition, Iino and Kojima (2009) found that advanced male players had a greater lower trunk axial rotation in generating racket velocities and tended to have less time for racket acceleration in performing forehand strokes compared to intermediate players. Iino et al. (2008) observed that the magnitudes of elbow and wrist angular velocities were similar between the backspin and topspin conditions, but their contributions to the racket velocity were different due to changes in joint angles in backhand strokes. Qian et al. (2016) observed that advanced players demonstrated greater hip flexion and knee external rotation near the beginning of the stroke and greater hip internal rotation near the end of the stroke. These findings suggest that the whole-body works as a chain to increase the velocity of the racket. Factors including stroke types and performance levels could affect joint and racket velocities.

Recently, Bankosz and Winiarski (2017) quantified the kinematics of the racket when young female players completed forehand or backhand strokes when returning balls with or without backspin. While peak racket velocities typically occurred at the time of impact, a forehand stroke with backspin balls at a 100% effort level resulted in the longest racquet trajectory. Additionally, the principle of proximal-to-distal sequences with the proximal joints initiating the angular motion earlier and the distal joints starting the angular motion later was found to achieve a high racket velocity (Bankosz and Winiarski, 2018b). Later, the authors found shoulder internal rotation and adduction velocities of the stroking arm were related to racket velocities in forehand strokes, while shoulder abduction and external rotation velocities of the stroking

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arm were associated with racket velocities in backhand strokes (Bankosz and Winiarski, 2018a). The results have highlighted the importance of certain joint angles and angular velocities in affecting racket velocities in specific strokes.

The grip style is another factor that may affect stroke kinematics and performance. The two commonly used grips are the shakehand and penhold grips. Although many Olympic champions used the penhold grip, a report showed that only 2 of the world's top-20 male players and none of the world's top-20 female players were using the penhold grip in 2017 (International Table Tennis Federation, 2017). Surprisingly, no studies have quantified the kinematic differences between the two grips to identify the potential advantages of each grip. The popularity of the shakehand grip could be the reason that only players using the shakehand grip were included in previous studies (Iino and Kojima, 2009; 2016; Iino et al., 2008; Bankosz and Winiarski, 2017; 2018a). However, whether the findings observed in the shakehand grip could be generalized to the penhold grip was unknown. Quantifying the kinematic differences between the shakehand and penhold grips can provide insight into grip choices, skill training, training exercises, and tactical strategies for beginners and advanced players.

Therefore, the purpose of this study was to compare the joint, racket, and ball kinematics between the shakehand and penhold grips in table tennis forehand and backhand strokes when returning topspin and backspin balls in advanced male players. Based on the popularity of the shakehand grip in elite players, it was hypothesized that the shakehand grip would result in increased peak racket and ball velocities in both forehand and backhand strokes when returning topspin and backspin balls compared to the penhold grip. In addition, it was hypothesized that the changes in peak racket and ball velocities would result from differences in joint angles and angular velocities.

Methods

Participants

A total of twenty-seven male table tennis players at the Chinese national level I or II participated. Participants included nine penhold-grip players, and each penhold-grip player was matched with two shakehand-grip players with similar heights, mass, ages, training experience, and national levels ($p > 0.05$, Table 1). All participants were right-handed and had no musculoskeletal injuries in the previous six months. This study followed the guidelines of the Declaration of Helsinki and was approved by the Institutional Review Board of China Table Tennis College. All participants signed an informed consent form prior to participation.

Table 1. Characteristic of the groups. Data are means (±SD).

Variables	Shakehand (n=18)	Penhold (n=9)
Height (m)	1.76 (0.05)	1.75 (0.5)
Mass (kg)	66.4 (8.0)	63.7 (7.8)
Age (yr)	19.7 (1.4)	20.4 (1.4)
Training experience (yr)	12.0 (2.0)	12.1 (2.1)

Procedure

Participants were refrained from any strenuous exercises within 24 hours prior to the study. Participants wore a spandex outfit and table tennis shoes as they did in training and competitions. Warm-up activities included 5 minutes of jogging on a treadmill at 2.5 m/s followed by 3 minutes of static stretching as well as 5 minutes of strokes.

Participants completed three successful topspin strokes with forehand (Figure 1 and 2) or backhand strokes when returning (Figure 3 and 4) topspin or backspin balls using their habitual grips. Additional practice for each stroke condition was allowed before the official trials. Participants stood on the left or right side of the table for backhand or forehand strokes, respectively (Figure 5). The incoming ball with topspin or backspin was served by a serving machine (Robot R2, DHS, Shanghai, China) placed 0.5 meter away from the middle of the opposite court, producing consistent serving angles, velocities, frequencies (25 balls per minute), ball placements (setting 2 for the position for forehand strokes; setting 10 for the position for backhand strokes), and spin directions (setting 5 for the top-wheel speed and setting 1 for the bottom-wheel speed for topspin balls; setting 1 for the top-wheel speed and setting 5 for the bottom-wheel speed for topspin balls). Once the ball was served, participants hit the ball using the required stroke technique in a straight line to the same side of the opposite court with a maximal effort (Figure 5). Participants were asked to repeat the trial if the ball did not hit the targeted area with a maximal effort. The order of the four-stroke conditions was randomized. Participants completed one stroke at a time with at least 30 seconds break between two trials.

Figure 1. Starting and final postures for forehand strokes with a shakehand grip.

Figure 2. Starting and final postures for forehand strokes with a penhold grip.

Figure 3. **Starting and final postures for backhand strokes with a shakehand grip.**

Figure 4. **Starting and final postures for backhand strokes with a penhold grip.**

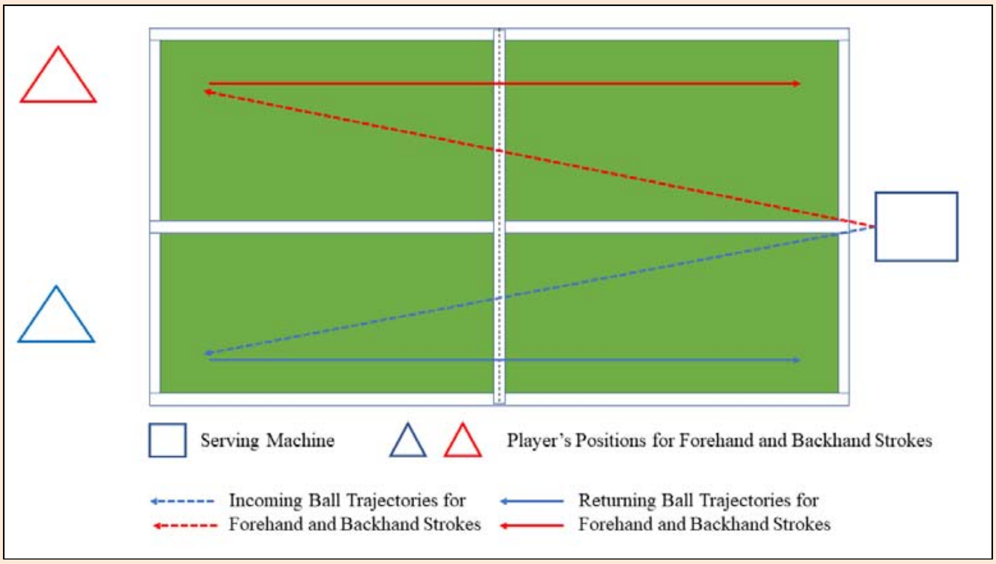

Figure 5. **Locations of the player and serving machine and trajectories of incoming and returning balls.**

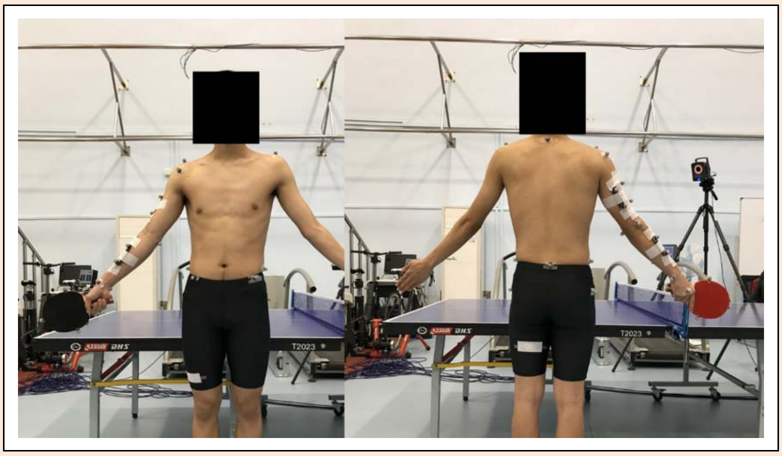

Figure 6. **Maker placements.**

Standard rackets (shakehand: 4002, DHS, Shanghai, China; penhold: 4006, DHS, Shanghai, China) with both sides of rubbers having pimples facing in were used. A total of 25 retro-reflective markers (14.0 mm diameter) were attached to the participant's body landmarks with double-sided adhesive tape to define the pelvis, trunk, as well as the upper arm and forearm of the stroking side (Figure 6). In addition, three markers were positioned at the top, left, and right edges of the racket. Kinematic data were collected at a sampling rate of 100 Hz using a 10-camera motion capture system (Vicon T40, Oxford Metrics, UK). A high-speed camera was placed perpendicular to the motion plane of the ball to record ball motion at a sampling frequency of 250 Hz to capture ball positions and velocities (Figure 7). Prior to the data collection, a linear scale was placed on the motion plane of the ball to calibrate the high-speed camera for the forehand and backhand strokes, respectively.

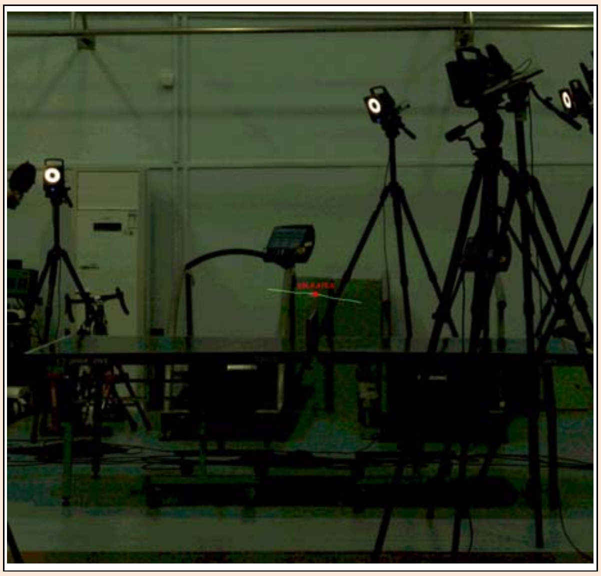

Figure 7. Digitization of ball trajectories for a backhand stroke.

Data reduction

One shakehand player was used to rubbers with long pimples facing out instead of pimples facing in for backhand strokes. While pimple-in rubbers were mostly used, long pimple-out rubbers were used by a small portion of players to modify the spin of the ball compared to other rubbers. Therefore, this player's backhand stroke data were not included for analysis. Marker position data were filtered using a Butterworth fourth-order zero-lag low-pass filter with a cutoff frequency of 15 Hz. The shoulder joint center was defined as the middle point of the greater and lesser tubercle of the humerus. The elbow joint center was defined as the middle point of medial and lateral epicondyles of the humerus. The wrist joint center was defined as the middle point of the medial and lateral radial and ulnar styloid processes. The pelvis was defined by the left and right anterior superior iliac crests and the middle point of the left and right posterior superior iliac crests. The middle-upper trunk was defined by the left and right shoulders and the 7th cervical vertebra. The upper arm was defined by the shoulder and elbow joint centers and the lateral epicondyles of the humerus. The forearm was defined by the elbow and wrist joint centers and the radial styloid processes. The racket was defined by the top, left, and right markers placed on it. Local segment coordinates were defined as x in the anterior-posterior direction, y in the medial-lateral direction, and z in the vertical direction when the participant was standing in the anatomical position. Cardan angles between the pelvis and middle-upper trunk segment coordinates were calculated to quantify trunk joint angles. Cardan angles between the middle-trunk segment and upper arm coordinates were calculated to quantify shoulder joint angles. Cardan angles between the upper arm and forearm coordinates were calculated to quantify elbow joint angles with the rotation around the z-axis as forearm pronation or supination. Cardan angles between the forearm and racket coordinates were calculated to quantify racket angles, which represented the resultant effects of the wrist joint motion and the motion between the hand and racket. The racket was not an anatomical joint. While the wrist had a large range of motion in flexion and extension and likely mainly contributed to racket flexion and extension, the relative motion between the racket and the hand might make substantial contributions to racket abduction and adduction as well as internal and external rotations. Racket angles were italicized because of its unconventional use in the current study. Cardan angles were calculated with an order of rotation of flexion-extension (y), adduction-abduction (x), and internal-external rotation (z). Joint angular velocities were calculated from joint angles using the first central difference method.

Two critical events were identified for the stroke motion. The first event was defined as the initiation of the stroke, quantified as the most backward position of the top marker of the racket in the global coordinate. The second event was defined as the peak resultant velocity of the racket, which has been shown to coincide with the time of ball impact (Bankosz and Winiarski, 2018a). Three-dimensional racket angles and selective joint angles, where were identified as main contributors and predictors of racket linear velocities (Bankosz and Winiarski, 2018a; Iino et al., 2008; Iino and Kojima, 2009), were extracted at both the initiation of the stroke and the peak resultant velocity of the racket. Racket and joint angular velocities were extracted at the peak resultant velocity of the racket. Videos captured by the high-speed cameras were manually digitized to quantify the ball's positions in the horizontal and vertical direction using the MaxTRAQ software (Innovision Systems Inc, Columbiaville, MI). Digitization included five frames before the ball passed the net, one frame when the ball passed the net, and five frames after the ball passed the net (Figure 7). The first central difference method was used to calculate the ball velocities of the 11 frames, and the averages of these velocities were used to represent ball forward and downward velocities.

Statistical analysis

Data of the three official trials were averaged for further analysis. Independent t-tests were used to compare the kinematic parameters between the shakehand and penhold groups for each of the four-stroke conditions. The statistical significance level was set 0.05 with p values between 0.05 and 0.1 indicating a trend towards significance. Statistical analyses were performed using the SPSS Statistics 24 software (IBM Corporation, Armonk, NY).

Results

For the forehand topspin and backspin conditions (Table 2), no significant differences were observed for ball or racket velocities between the two grips. The shakehand grip tended to demonstrate a shorter time to reach peak racket resultant velocity and greater shoulder external rotation angles compared to the penhold grip. While the racket was generally in the neutral but *externally rotated* position for the shakehand grip, the racket was in *adduction, flexion,* and more *externally rotated* position for the penhold grip. The shakehand grip resulted in racket *flexion* angular velocity compared to racket *extension* velocity for the penhold grip. The penhold grip tended to demonstrate increased racket *internal rotation* angular velocity.

For the backhand topspin and backspin conditions (Table 3), greater ball and racket velocities and shorter times to reach peak racket velocity were generally observed for the shakehand grip. The shakehand grip generally demonstrated decreased final trunk left rotation angles, increased trunk right rotation angular velocities, decreased final shoulder abduction angles, increased shoulder adduction angular velocities, and increased forearm supination angular velocities. The racket was in *abduction* and less *flexion* and showed *adduction* velocities for the shakehand grip, while the racket was in *adduction* and greater *flexion* and showed racket *abduction* angular velocities for the penhold grip. The racket *extension* velocities were the greatest among all the joint angular velocities with the shakehand grip demonstrating greater velocities than the penhold grip for the backspin condition.

Discussion

The purpose of this study was to compare joint, racket, and ball kinematics between the shakehand and penhold grips in table tennis forehand and backhand strokes when returning topspin and backspin balls in advanced male players. The observed peak racket and ball velocities in forehand and backhand strokes with the shakehand grip were similar to previous findings in advanced male athletes (Iino and Kojima, 2009, Iino et al., 2008), suggesting comparable performance levels and techniques.

The findings do not support the hypothesis that the shakehand grip would result in increased peak racket and ball velocities in forehand strokes when returning topspin and backspin balls compared to the penhold grip, although different joint kinematics have been observed. Iino and Kojima (2009) showed that shoulder internal rotation and flexion angular velocities made the most contributions, while forearm and wrist angular velocities had small contributions to racket velocities at the time of ball impact in forehand strokes. Consistently, shoulder internal rotation and flexion angular velocities represented the two greatest angular velocities in the current study, supporting the major role of the shoulder in producing racket velocities in forehand strokes. As shoulder, angular velocities were similar between the two grips, their effects

Table 2. Means (standard deviations) for the two grips for forehand topspin and backspin strokes.

Variables	Forehand Topspin		Forehand Backspin	
	Shakehand (n=18)	Penhold (n=9)	Shakehand (n=18)	Penhold (n=9)
Ball forward (+) velocity (m/s)	16.10 (1.13)	15.89 (1.45)	14.52 (1.10)	14.37 (0.78)
Ball downward velocity (-) (m/s)	-1.80 (-0.26)	-1.72 (-0.16)	-1.41 (-0.27)	-1.40 (-0.27)
Peak racket resultant velocity (m/s)	18.62 (1.51)	18.15 (1.33)	18.76 (1.52)	18.37 (1.89)
Timing of peak racket resultant velocity (s)	0.11 (0.01)	0.14 (0.04) *	0.11 (0.02)	0.12 (0.04)
Initial trunk right rotation (-) angle (°)	-19.86 (11.76)	-11.34 (12.01)	-16.35 (12.41)	-8.37 (11.94)
Final trunk right rotation (-) angle (°)	-5.99 (7.15)	-2.33 (7.29)	-6.08 (8.13)	-2.77 (7.47)
Trunk left (+) rotation angular velocity (°/s)	154.2 (169.0)	145.0 (67.7)	97.1 (193.5)	74.1 (83.5)
Initial shoulder abduction (-) angle (°)	-22.51 (8.62)	-28.00 (6.88)	-21.85 (7.90)	-27.25 (8.66)
Final shoulder abduction (-) angle (°)	-43.72 (7.64)	-48.35 (8.36)	-41.16 (6.21)	-45.20 (9.05)
Shoulder adduction (+) / abduction (-) angular velocity (°/s)	-34.53 (161.52)	42.77 (220.86)	-3.78 (166.88)	13.63 (194.06)
Initial shoulder flexion (-) angle (°)	-15.40 (19.33)	-16.35 (18.39)	-14.44 (18.66)	-12.73 (20.52)
Final shoulder flexion (-) angle (°)	-57.07 (16.81)	-60.66 (17.72)	-60.61 (17.90)	-59.57 (19.60)
Shoulder flexion (-) angular velocity (°/s)	-802.5 (268.8)	-953.6 (281.8)	-775.4 (248.7)	-998.6 (332.0)
Initial shoulder external rotation (-) angle (°)	-42.62 (10.72)	-27.88 (19.81) *	-43.50 (10.41)	-33.80 (16.52)
Final shoulder internal (+) / external (-) rotation angle (°)	-9.88 (14.78)	6.94 (18.63) *	-6.84 (13.43)	5.49 (19.35)
Shoulder internal (+) rotation angular velocity (°/s)	1096.6 (237.8)	1082.1 (340.8)	1099.0 (236.3)	1077.1 (336.8)
Initial elbow flexion (-) angle (°)	-55.73 (15.11)	-56.11 (15.91)	-56.54 (16.60)	-55.67 (19.46)
Final elbow flexion (-) angle (°)	-59.09 (14.74)	-53.33 (15.09)	-59.89 (14.97)	-56.22 (18.18)
Elbow flexion (-) angular velocity (°/s)	-72.15 (172.66)	-176.18 (149.32)	-78.80 (204.59)	-191.12 (191.99)
Initial forearm pronation (+) angle (°)	129.6 (18.0)	137.0 (16.2)	130.3 (20.1)	133.0 (17.7)
Final forearm pronation (+) angle (°)	132.4 (14.2)	136.7 (16.7)	133.1 (14.6)	137.6 (16.6)
Forearm pronation (+) angular velocity (°/s)	98.5 (180.7)	213.6 (111.1)	102.1 (210.3)	207.3 (116.8)
Initial racket *adduction* (+) angle (°)	6.59 (13.96)	44.98 (11.13) #	8.13 (14.38)	45.66 (11.38) #
Final racket *adduction* (+) / abduction (-) angle (°)	2.66 (12.73)	34.70 (9.28) #	2.35 (13.14)	32.98 (10.20) #
Racket *adduction* (+) / *abduction* (-) angular velocity (°/s)	-175.6 (75.3)	-212.7 (121.5)	-191.7 (94.1)	-194.9 (108.6)
Initial racket *extension* (+) / *flexion* (-) angle (°)	1.99 (19.38)	-48.28 (23.87) #	2.35 (21.16)	-45.97 (25.84) #
Final racket *extension* (+) / *flexion* (-) angle (°)	0.38 (14.17)	-33.28 (17.52) #	0.02 (14.20)	-33.19 (15.43) #
Racket *extension* (+) / *flexion* (-) angular velocity (°/s)	-47.8 (102.1)	196.1(99.6) #	-26.9 (121.1)	189.1 (116.7) #
Initial racket *external rotation* (-) angle (°)	-28.65 (18.63)	-79.10 (15.14) #	-28.33 (19.76)	-79.17 (17.29) #
Final racket *external rotation* (-) angle (°)	-31.32 (16.16)	-72.13 (12.43) #	-31.25 (16.79)	-70.14 (12.62) #
Racket *internal (+) rotation* angular velocity (°/s)	13.23 (87.14)	106.88 (78.35) *	16.49 (101.37)	88.21 (90.30)

Initial joint angles were extracted at the initiation of the forward stroke. Final joint angles and angular velocities were extracted at the time of the peak racket resultant velocity. * $p < 0.05$, # $p < 0.001$.

Table 3. Means (standard deviations) for the two grips for backhand topspin and backspin strokes.

Variables	Backhand Topspin		Backhand Backspin	
	Shakehand (n=18)	Penhold (n=9)	Shakehand (n=18)	Penhold (n=9)
Ball forward (+) velocity (m/s)	16.13 (0.95)	15.11 (0.78) *	14.63 (1.15)	13.71 (0.92) *
Ball downward velocity (-) (m/s)	-2.04 (-0.22)	-1.93 (-0.25)	-1.61 (-0.18)	-1.35 (-0.21) †
Peak racket resultant velocity (m/s)	17.04 (1.37)	14.55 (1.18) #	17.86 (1.36)	15.36 (1.09) #
Timing of peak racket resultant velocity (s)	0.13 (0.02)	0.15 (0.02) †	0.13 (0.03)	0.16 (0.03) *
Initial trunk left rotation (+) angle (°)	17.83 (6.55)	21.74 (5.34)	16.73 (4.66)	19.36 (5.26)
Final trunk left rotation (+) angle (°)	7.31 (7.35)	17.47 (4.98) #	4.15 (6.45)	14.20 (6.58) #
Trunk left (+) / right (-) rotation angular velocity (°/s)	-101.6 (98.04)	2.48 (88.50) *	-128.2 (99.14)	-15.87 (80.20) †
Initial shoulder abduction (-) angle (°)	-38.44 (6.75)	-34.67 (6.58)	-40.28 (6.81)	-36.80 (7.33)
Final shoulder abduction (-) angle (°)	-30.91 (9.48)	-40.91 (8.93) *	-27.36 (9.85)	-34.84 (8.36)
Shoulder adduction (+) angular velocity (°/s)	112.25 (119.43)	20.15 (100.92)	159.55 (95.72)	76.46 (130.78)
Initial shoulder flexion (-) angle (°)	-47.83 (13.01)	-45.38 (10.68)	-44.08 (14.09)	-42.62 (8.78)
Final shoulder flexion (-) angle (°)	-84.50 (10.76)	-78.58 (13.75)	-83.05 (12.19)	-79.95 (15.83)
Shoulder flexion (-) angular velocity (°/s)	-229.53 (133.71)	-315.27 (188.66)	-210.28 (122.03)	-269.36 (181.77)
Initial shoulder internal rotation (+) angle (°)	66.12 (16.40)	59.82 (14.72)	64.59 (16.95)	55.80 (13.92)
Final shoulder internal (+) rotation angle (°)	55.63 (11.62)	46.92 (14.90)	57.22 (12.09)	45.23 (9.36) *
Shoulder external (-) rotation angular velocity (°/s)	-726.02 (202.98)	-498.06 (394.52)	-829.12 (227.21)	-766.64 (332.10)
Initial elbow flexion (-) angle (°)	-83.23 (5.73)	-84.79 (11.98)	-77.10 (8.18)	-78.76 (12.77)
Final elbow flexion (-) angle (°)	-55.43 (9.39)	-62.52 (10.15)	-55.52 (9.80)	-58.45 (9.78)
Elbow extension (+) angular velocity (°/s)	558.64 (140.19)	619.45 (167.95)	419.42 (176.97)	451.41 (170.42)
Initial forearm pronation (+) angle (°)	87.52 (17.39)	79.95 (13.98)	88.08 (21.00)	85.71 (14.77)
Final forearm pronation (+) angle (°)	74.08 (17.65)	71.33 (13.76)	73.46 (18.76)	72.54 (12.51)
Forearm supination (-) angular velocity (°/s)	-422.60 (335.01)	-41.91 (309.07) †	-610.53 (402.54)	-319.97 (296.21)
Initial racket *adduction* (+) / *abduction* (-) angle (°)	-27.72 (16.73)	23.45 (15.63) #	-28.86 (17.21)	20.36 (13.85) #
Final racket *adduction* (+) / *abduction* (-) angle (°)	-21.15 (10.07)	11.17 (10.81) #	-20.74 (10.32)	9.38 (9.38) #
Racket *adduction* (+) / *abduction* (-) angular velocity (°/s)	328.61 (350.26)	-97.80 (146.89) †	244.62 (320.05)	-82.96 (147.04) †
Initial racket *flexion* (-) angle (°)	-47.48 (16.88)	-96.10 (21.35) #	-47.00 (15.67)	-88.87 (27.77) #
Final racket *flexion* (-) angle (°)	-9.93 (12.55)	-52.58 (15.11) #	-7.03 (12.06)	-44.24 (14.01) #
Racket *extension* (+) angular velocity (°/s)	1252.6 (380.1)	1042.7 (358.2)	1347.1 (447.5)	828.5 (314.4) †
Initial racket *external rotation* (-) angle (°)	-66.36 (9.15)	-62.41 (9.14)	-66.97 (9.27)	-58.57 (12.64)
Final racket *external rotation* (-) angle (°)	-70.13 (13.27)	-59.96 (9.08)	-69.50 (13.58)	-61.03 (9.00)
Racket *external (-) rotation* angular velocity (°/s)	-135.58 (203.01)	-107.55 (149.48)	-201.20 (197.74)	-200.29 (111.89)

Initial joint angles were extracted at the initiation of the forward stroke. Final joint angles and angular velocities were extracted at the time of the peak racket resultant velocity. * $p < 0.05$, † $p < 0.01$, # $p < 0.001$.

on racket and ball velocities were likely similar and contributed to the non-significant peak racket and ball velocities between the two grips. However, since the racket was in a more externally rotated position, the penhold grip compensated with decreased shoulder external rotation throughout the stroke to place the racket in the desired plane for ball impact. Despite different initial and final shoulder external rotation angles, both grips utilized similar shoulder external rotation joint range of motion to produce comparable peak angular velocities. Regarding racket kinematics, the different racket angles between the two grips were inherently associated with the relative position of the racket to the forearm. However, the more *externally rotated* and *flexed* racket for the penhold grip allowed greater racket *internal rotation* and *extension* velocities for generating racket velocities. On the other hand, a close to neutral racket position for the shakehand grip involved racket *flexion* velocities. In summary, the two grips demonstrated similar peak racket and ball velocities in forehand strokes, but they engaged different shoulder external rotation and utilized different racket movements in relation to the forearm.

The findings support the hypothesis that the shakehand grip would result in increased peak racket and ball velocities in backhand strokes when returning topspin and backspin balls compared to the penhold grip. The shakehand grip also demonstrated a shorter time to reach peak racket velocities. Literature has shown that the mechanism to increase racket velocities was different for backhand strokes with the angular velocities of wrist extension, elbow extension, and shoulder external rotation making the greatest contributions (Iino et al., 2008). Similarly, the greatest angular velocities were found for racket *extension*, shoulder external rotation, and elbow extension in the current study. The shakehand grip demonstrated increased racket *extension* angular velocities for the backspin condition and tended to have greater shoulder external rotation angular velocities for the topspin condition, supporting the grip style had a direct effect on the major contributors to racket linear velocities (Iino et al., 2008). The shakehand grip also showed increased angular velocities of trunk right rotation, shoulder adduction, and forearm supination. Both grips started with the racket pointed backward and placed close to the transverse plane. Compared to the penhold grip with the hand holding the racket below, the hand was along with the handle for the shakehand grip. With the same starting racket position, the elevated shakehand grip resulted in increased shoulder abduction and internal rotation and forearm pronation. The increased initial shoulder abduction allowed greater shoulder adducting motion throughout the stroke and likely resulted in the increased shoulder adduction angular velocities for the shakehand-grip. On the other hand, the shoulder abduction slightly increased or remained similar for the penhold grip, suggesting the limited role of shoulder adducting motion in producing linear racket velocities.

Also, the shakehand- grip tended to engage greater shoulder internal rotation angles throughout the stroke, which might provide a better range of motion to develop shoulder external rotation angular velocities compared to the penhold-grip. Furthermore, the increased forearm pronation increased the forearm supination range of motion and supination angular velocities when striking topspin balls for the shakehand grip. For racket kinematics, the racket started with *flexion* and ended with small *flexion* near the ball impact for the shakehand grip. This close alignment between the longitudinal axes of the racket and the forearm might facilitate the transfer from the angular velocities of trunk right rotation, shoulder adduction and external rotation, and racket *extension* to racket linear velocities in the forward direction. On the other hand, the transfer of these angular velocities could be less because of the increased flexion between the racket and forearm for the penhold grip. This increased flexion could also increase the demand for controlling the effects of different joint motion on racket orientation and had affected the players to decrease their speeds for better movement control. Overall, the penhold grip resulted in decreased peak racket and ball velocities compared to the shakehand grip. The penhold grip involved different joint angles and range of motion of shoulder abduction, shoulder internal rotation, and forearm pronation, which may have affected the development of the angular velocities of these joints. The penhold grip also involved less aligned longitudinal axes between the racket and forearm, which might have decreased joint angular velocities and the transfer from joint angular velocities to racket linear velocities.

The current findings may provide information for practical application. For advanced players who have chosen either the shakehand or penhold grip, they should be aware of the different shoulder joint range of motion and racket motion involved for the forehand strokes and perform designed exercises target specific movements and muscle groups. Players with the penhold grip need to understand the potential disadvantages associated with the decreased shoulder, elbow, and forearm motion and the less aligned longitudinal axes between the racket and forearm in backhand strokes. Being able to develop shoulder, elbow, forearm, and racket angular velocities with a smaller range of motion is crucial for these players. For beginners, they may consider the increased racket velocities in backhand strokes for the shakehand grip, as an advantage for grip selection. This factor could also help them understand the dominance of the shakehand grip over the penhold grip in elite athletes. In addition, the shakehand had a more neutral alignment between the racket and forearm, and mainly involved racket flexion and extension, which may facilitate learning in the early stage.

The current study had several limitations. First, the time of ball impact was not measured. Instead, the peak racket velocity was used as a critical event to extract kinematic variables. Although previous studies have supported that the peak racket velocity typically occurs at ball impact (Bankosz and Winiarski, 2018a), this estimation might have introduced errors. In addition, the peak angular velocities of different joints could occur before the peak resultant velocity of the racket, but the angular velocities at this critical event were expected to have a more direct effect on the peak resultant velocity of the racket. Second, only one marker was placed on the hand, so the three-dimensional angles between the hand and the racket and between the hand and the forearm could not be quantified. The separation of the wrist motion from the racket motion should be considered in follow-up studies. Third, the direction and speed of the ball's rotation were not measured. The penhold involved greater racket motion in non-sagittal planes, which could have a greater influence on ball rotation. Fourth, strokes were performed with a consistent serve and a pre-determined trajectory of return with an effort to achieve maximal ball velocities. Other factors, such as directions and depths of return and movement deception, could affect the outcome of a rally in real competitions. It is possible that the more flexed alignment between the racket and forearm for the penhold grip might help prevent opponents from detecting planned movements. Fifth, the participants were limited to male players. Future studies should examine the two grips in female players to identify potential sex differences. Last, the current study was limited to joint, racket, and ball kinematics. Previous studies have applied kinetic analyses (Iino, 2018; Iino and Kojima, 2011; 2016), which should be considered in future studies.

Conclusion

The shakehand and penhold grips demonstrated similar peak racket and ball velocities but different shoulder rotation range of motion and racket motion in relation to the forearm in forehand strokes. The penhold grips resulted in decreased peak racket and ball velocities compared to the shakehand grip in backhand strokes. This could be due to its decreased shoulder, elbow, and forearm motion as well as less aligned longitudinal axes between the racket and forearm, which might have decreased joint angular velocities and the transfer from joint angular velocities to racket linear velocities. These results may help understand the dominance of the shakehand grip over the penhold grip in elite athletes. Advanced players and beginners may consider these findings for grip selection, technique improvements, and exercise training.

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Key points

- The shakehand and penhold grips demonstrated similar peak racket and ball velocities but different shoulder and racket motion in relation to the forearm in forehand strokes.
- The penhold grips resulted in decreased peak racket and ball velocities compared to the shakehand grip in backhand strokes.
- For backhand strokes, the penhold had decreased shoulder, elbow, and forearm motion as well as less aligned longitudinal axes between the racket and forearm, which might result in the decreased racket velocities.
- The findings may help understand the dominance of the shakehand grip over the penhold grip in elite athletes.
- Advanced players and beginners may consider these findings for grip selection, technique improvements, and exercise training.

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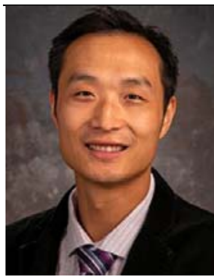

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