

Research article

Comparing the Kinematic Characteristics of the Lower Limbs in Table Tennis: Differences between Diagonal and Straight Shots Using the Forehand Loop

Yuqi He¹, Xiang Lv¹, Zhexiao Zhou¹, Dong Sun¹, Julien S. Baker² and Yaodong Gu¹✉

¹ Faculty of Sports Science, Ningbo University, Ningbo, China

² Department of Sport, and Physical Education, Hong Kong Baptist University, Hong Kong, China

Abstract

The diagonal shot (DS) and straight shot (SS) using the forehand loop are the most common techniques used in table tennis. The purpose of this study was to investigate the kinematic differences of the lower limbs between DS and SS. Twelve male table tennis athletes performed DS and SS in random order. Kinematic data were captured using a three-dimensional Vicon motion analysis system. The major findings of this study were that DS showed significantly less time compared with SS during the backward swing (BS) and the forward swing (FS) phases. Meanwhile, DS showed significantly larger ankle internal rotation and inversion with smaller knee abduction and external rotation during the BS. DS showed significantly larger knee extension with smaller hip adduction and knee internal rotation compared with SS during the FS. However, SS showed a significantly larger range of motion (ROM) of ankle plantar flexion external rotation, and significantly larger ROM of knee extension. Moreover, SS showed significantly larger knee internal rotation compared with DS. These differences between the two shot techniques could be beneficial for helping coaches and table tennis athletes optimize performance, both in training and competition.

Key words: Table tennis, forehand loop, shot techniques, kinematic.

Introduction

Table tennis is one of the most popular racket sports in the world. Among various table tennis techniques, the forehand loop is considered as one of the most frequent and aggressive strokes in competitions, which can be applied to hit the ball at a high velocity with a fast rotation (Qian et al., 2016; Poizat et al., 2004). Performing a perfect topspin forehand stroke is difficult, and it is an important factor to recognize the performance levels of the players (Iino and Kojima, 2011). Investigating the biomechanical characteristics of a topspin forehand stroke is necessary as it could help athletes and coaches better understand the internal mechanisms and further improve performance.

To date, few studies have investigated the kinematic characteristics of the lower limbs during the forehand loop. This technique is relatively complex, and it involves multi-joint movements. Iino and Kojima (2011) demonstrated that higher angular speed and greater energy transduction from the pelvis to the racket handle, in combination with rotation of the upper body could contribute to the perfect shot. By quantifying the joint forces and torques of the racket handle as well as gross mechanical energy produced and transferred to the handle during topspin forehand, they

found that the internal rotation torque of the shoulder exerted by professional athletes was significantly larger. This helped promote the energy transfer from the trunk to arm at a higher rate (Qian et al., 2016). In addition, both the greater contribution of lower trunk axial rotation during ball impact and larger energy transduction from the pelvis to shoulder have also been reported in professional athletes when compared to their amateur counterparts (Iino and Kojima, 2011).

Some studies have investigated the effects of different ball speed or performance levels on the stroke performance from the biomechanical perspective (Bootsma and van Wieringen, 1990; Marinovic et al., 2004; Yu et al., 2018). High-quality forehand loop performance not only demands excellent upper body coordination but also requires support from the lower limbs to improve stability and accuracy during competitions (Yu et al., 2018). Le Mansec et al. (2018) compared the muscle activity of the lower limbs during seven typical table tennis strokes, in which they found that the forehand smash and top stroke techniques exhibited significantly higher EMG amplitudes compared with other strokes. Qian et al. (2016) indicated that elite athletes possessed a stronger ability to exert lower limb drive in the forehand loop when compared with intermediate players. Malagoli Lanzoni et al. (2018) found that differences in kinematics existed between the long-line and cross-court topspin forehand in table tennis players. Significant differences were detected for lower-limb angles, with larger mean angles among the feet - the table - pelvic rotation angles in the long-line compared with cross-court. Their results seemed to indicate that the feet position with respect to the table might have a main effect on the kinematics of both the cross-court and long-line executions. Nevertheless, their study did not specify the angle change rate of lower-limb joints in the long-line and cross-court top spin forehand batting modes. Furthermore, these studies have not explored the lower-limb kinematic characteristics when hitting the ball in different directions using the forehand loop techniques. Therefore, this study aimed to compare the lower-limb kinematic characteristics between diagonal shots (DS) and straight shots (SS) when using the forehand loop.

Methods

Participants

Twelve professional male table tennis athletes (age: 22.5 ± 1.4 years, body mass: 70.3 ± 3.9 kg, body height: 1.76 ± 0.05 m, training experience: 10.4 ± 1.4 years) volunteered

to participate in this test. All the subjects were members of the table tennis team at Ningbo University, Ningbo, China. They were all National Division I athletes, one of which had been the previous winner of the world table tennis championship on two occasions. All participants were right-handed with no previous lower limb injury or deformity for at least three months before the test. The handedness of these athletes was confirmed based on which hand was used to hold the racket (Peters and Murphy, 1992). All participants were asked to refrain from caffeine for at least 4 hours before the test, and all subjects completed experimentally informed agreements. The study was approved by the Human Ethics Committee of Ningbo University.

Experimental procedures

An 8-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data at a frequency of 100 Hz. Sixteen reflective markers (diameter: 14 mm) were attached with adhesive on bilateral lower limbs respectively. The marker locations included: anterior superior iliac spine, posterior-superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, second metatarsal head and calcaneus (Qian et al., 2016).

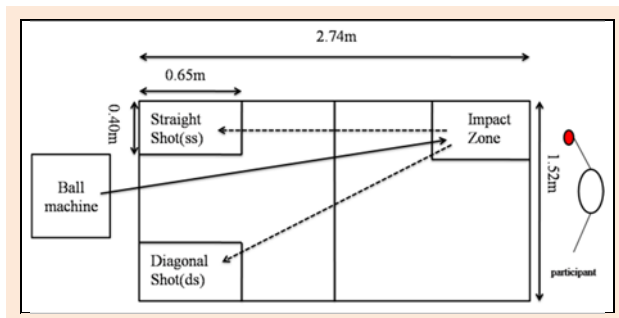


Figure 1. Experimental set-up (DS, Diagonal shot; SS, Straight shot)

Figure 1 outlined the experimental process which included two target zones (40×65cm) traced upon a regular playing table (Rainbow, Double Happiness Sports Company, Shanghai, China) (Malagoli Lanzoni et al., 2018). Before the test, the participants were asked to impact balls (D40+, Double Happiness Sports Company, Shanghai, China) projected by a robot ball machine (TaiDe V-989E, TaiDe Company, Hong Kong, China), to ensure that all participants were familiar with the experimental environment and had an adequate warm-up. Then, the participants performed diagonal and straight forehand loop shots at their maximum effort toward the two target areas placed on the other side of the table (Figure 1). The robot ball machine was set at a constant speed (level 8) and frequency (level 1). The participants were asked to start with a set of SS or DS randomly, with a three-minute break between each set. All trials were recorded until the player performed 5 shots on the left target (SS) and 5 on the right target (DS) accurately. During the experiment, all the participants wore the same table tennis shoes and used the same table tennis racket (Timoboll-zlc, Butterfly Technical Center, Tokyo,

Japan) with the Butterfly energy 05 Max (Butterfly Technical Center, Tokyo, Japan) and DHC Hurricane 3 (Double Happiness Sports Company, Shanghai, China) rubber sheets. The smoothness of motion was judged by players themselves and the quality of shot was supervised by coaches.

Data processing

The forehand loop motion was divided into two phases, backward swing (BS) and forward swing (FS). The BS phase referred to the period between neutral position (NP) and backward-end (BE, maximum knee flexion), while the FS phase referred to the period between BE and forward-end (FE, maximum hip internal rotation). The lower-limb joint angles, range of motion (ROM), and angular changing rate in three planes, as well as motion time were processed for further analysis.

Statistical analysis

SPSS version 19.0 software (SPSS Inc., Chicago, IL, USA) was applied for all the statistical analyses. The normality distribution of variables was verified with the Shapiro-Wilks normality test. To examine the kinematic differences between the two types of forehand loop shot, an independent T-test was taken for each variable including the motion time, joint angles, ROM and angular changing rate. The significance level was set at 0.05.

Results

Motion time

As shown in Table 1, DS showed significantly less time compared with SS during the BS and FS phases.

Table 1. Comparison of time at the phase of BS and FS between DS and SS (unit: second).

Variables	DS	SS	P-Value
	Mean ± SD	Mean ± SD	
BS phase	0.4 ± 0.1	0.4 ± 0.1	0.0*
FS phase	0.5 ± 0.1	0.6 ± 0.1	0.0*
Entire phase	1.0 ± 0.1	1.0 ± 0.2	0.0*

BS, backward-swing; FS, forward-swing; DS, diagonal shot; SS, straight shot. * indicates a significant difference at the DS and SS.

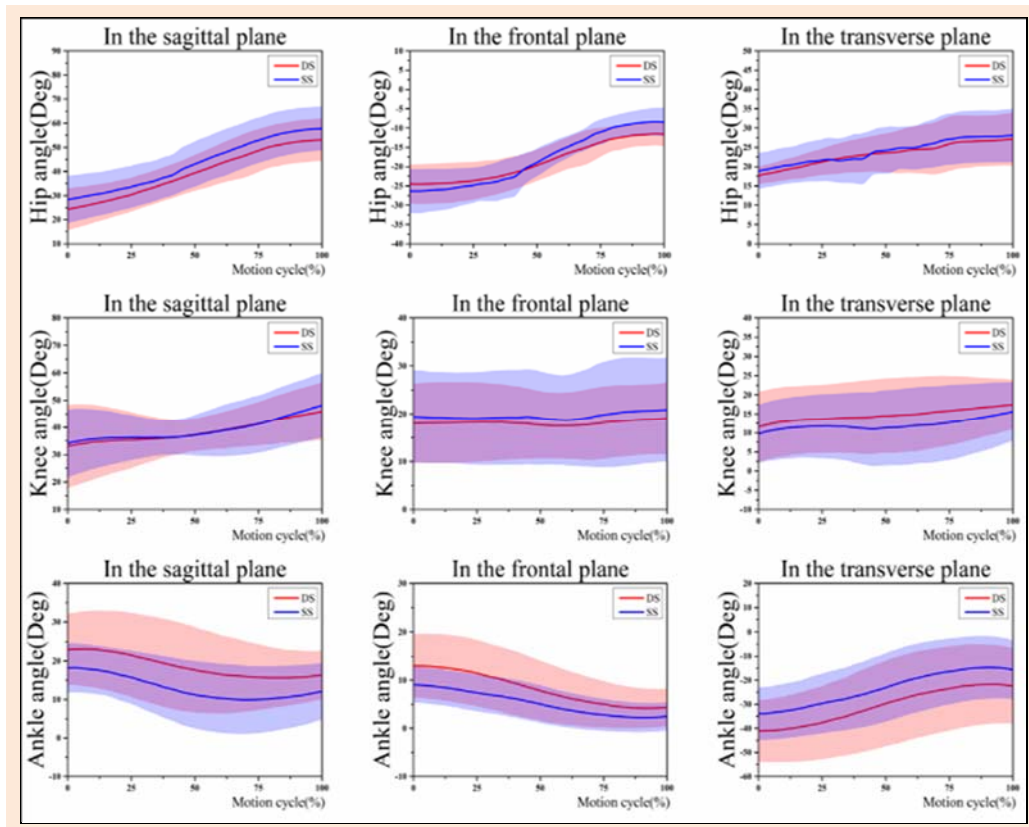
Lower-limb joint angle

Joint angles at BE and FE in the sagittal, frontal and transverse planes of DS and SS are presented in Table 2. Changes of joint angles during BS and FS phases in the sagittal, frontal and transverse planes of both DS and SS were generally comparable (Figure 2 and Figure 3). Significant differences in joint angles for the whole phase between DS and SS were found in the frontal plane and the transverse planes. In the BS phase, significant differences in joints angles of the knees and ankles between DS and SS were found in the frontal plane and transverse planes. Compared with SS, DS showed significantly larger ankle internal rotation and inversion while smaller knee abduction and external rotation. In the FS phase, DS showed significantly larger knee extension compared with SS. In addition, SS showed larger hip adduction and knee internal rotation compared with DS.

Table 2. Comparison of joints angles at key events between DS and SS (unit: degrees). Data are means (\pm SD).

Variables	ANKLE		KNEE		HIP	
	BE	FE	BE	FE	BE	FE
X(DS)	16.3 \pm 6.3	17.6 \pm 11.1	45.4 \pm 10.9	40.6 \pm 20.7*	52.8 \pm 9.1	6.1 \pm 14.4
X(SS)	13.3 \pm 7.2	15.9 \pm 11.5	44.8 \pm 11.7	40.4 \pm 23.1*	55.2 \pm 9.1	9.8 \pm 13.9
Y(DS)	4.3 \pm 3.8*	16.2 \pm 6.3	19.2 \pm 7.6*	25.0 \pm 7.1	-11.8 \pm 3.2	-27.8 \pm 7.7*
Y(SS)	2.8 \pm 2.7*	13.1 \pm 5.1	19.2 \pm 9.8*	23.2 \pm 7.9	-8.4 \pm 3.5	-28.3 \pm 6.7*
Z(DS)	-22.6 \pm 15.6*	-47.2 \pm 11.0	17.6 \pm 6.7*	8.8 \pm 6.9*	27.1 \pm 6.8	12.3 \pm 3.2
Z(SS)	-18.1 \pm 12.4*	-43.1 \pm 11.5	17.6 \pm 8.3*	10.2 \pm 5.3*	28.2 \pm 6.3	12.5 \pm 3.5

x—the sagittal plane; y—the frontal plane; z—the transverse plane. BE, backward-end; FE, forward-end; DS, diagonal shot; SS, straight shot. * indicates a significant difference at the hip, knee, and ankle (respectively) ($p < 0.05$).

**Figure 2.** Changes of the lower limb joints angle during the BS phase in three planes.**Table 3.** Comparison of ROM at the phase of BS and FS between DS and SS (unit: degrees). Data are means (\pm SD).

Variables	ANKLE		KNEE		HIP	
	BS	FS	BS	FS	BS	FS
X(DS)	10.7 \pm 3.4*	17.3 \pm 6.4*	19.0 \pm 8.0	16.4 \pm 4.7*	29.3 \pm 10.0*	46.4 \pm 8.8
X(SS)	9.6 \pm 4.4*	17.5 \pm 5.0*	20.6 \pm 6.7	19.5 \pm 6.5*	30.5 \pm 7.7*	45.3 \pm 8.1
Y(DS)	9.3 \pm 3.1*	13.9 \pm 5.1	5.4 \pm 1.5	9.3 \pm 2.8*	13.8 \pm 4.8	21.4 \pm 4.9
Y(SS)	7.6 \pm 2.2*	11.1 \pm 4.7	6.7 \pm 2.0	8.4 \pm 2.5*	18.0 \pm 3.8	23.3 \pm 4.9
Z(DS)	20.4 \pm 4.7	26.0 \pm 6.6*	12.7 \pm 3.5	13.1 \pm 5.9	10.2 \pm 5.7	16.7 \pm 6.6
Z(SS)	20.6 \pm 5.8	26.1 \pm 11.2*	14.3 \pm 4.2	13.8 \pm 7.0	11.9 \pm 5.1	17.6 \pm 6.2

x—the sagittal plane; y—the frontal plane; z—the transverse plane. BS, backward-swing; FS, forward-swing; DS, diagonal shot; SS, straight shot. * indicates a significant difference at the hip, knee, and ankle (respectively) ($P < 0.05$).

Range of motion

Lower-limb ROM during the BS and FS phases also showed significant differences between DS and SS (Table 3). In the BS phase, compared with SS, DS showed significantly larger ROM of the ankle joint in the sagittal and frontal plane, and the hip joint in the sagittal plane. In the FS phase, compared with SS, DS showed significantly smaller ROM of the ankle joint in the sagittal and transverse plane, and the knee joint in the sagittal planes. In addition, DS showed significantly larger ROM in the frontal plane of the knee joint compared with SS.

Angular changing rate

The angular changing rate at BS and FS phase between DS and SS in three planes are shown in Table 4 and Figure 4. The angular changing rate at the hip and ankle joints for the DS during BS phase were significantly larger in the sagittal and frontal plane, while smaller at the hip and knee joints rate was significantly larger for the knee joint in the frontal plane and ankle in the transverse plane, while smaller at the hip joint in the frontal plane during FS phase for DS.

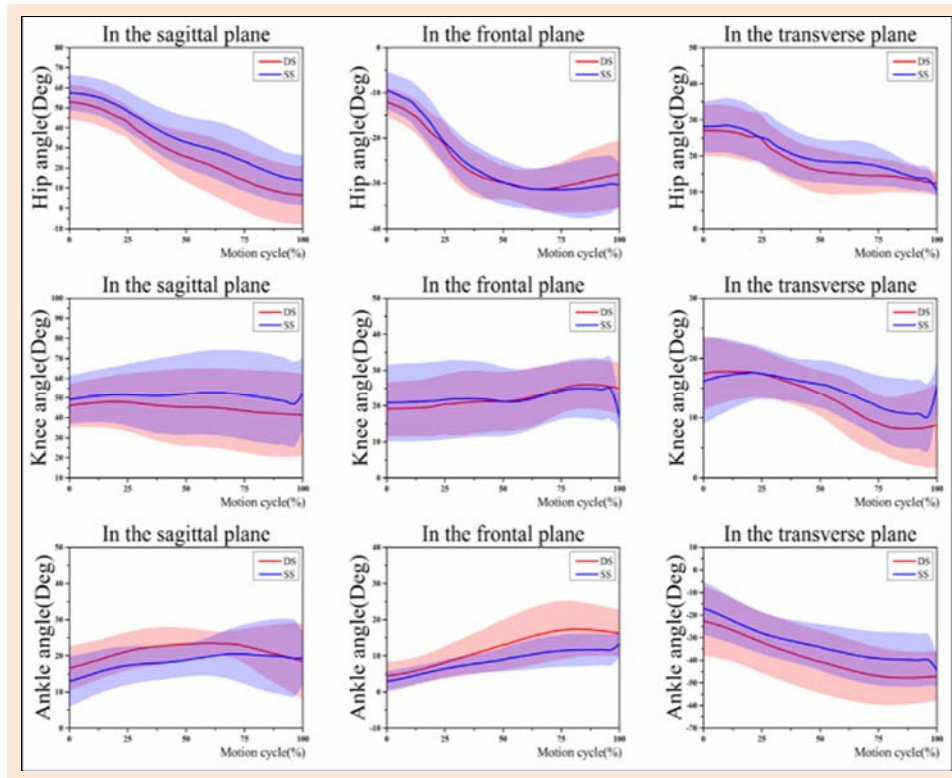


Figure 3. Changes of lower limb joints angle during FS phase in three planes.

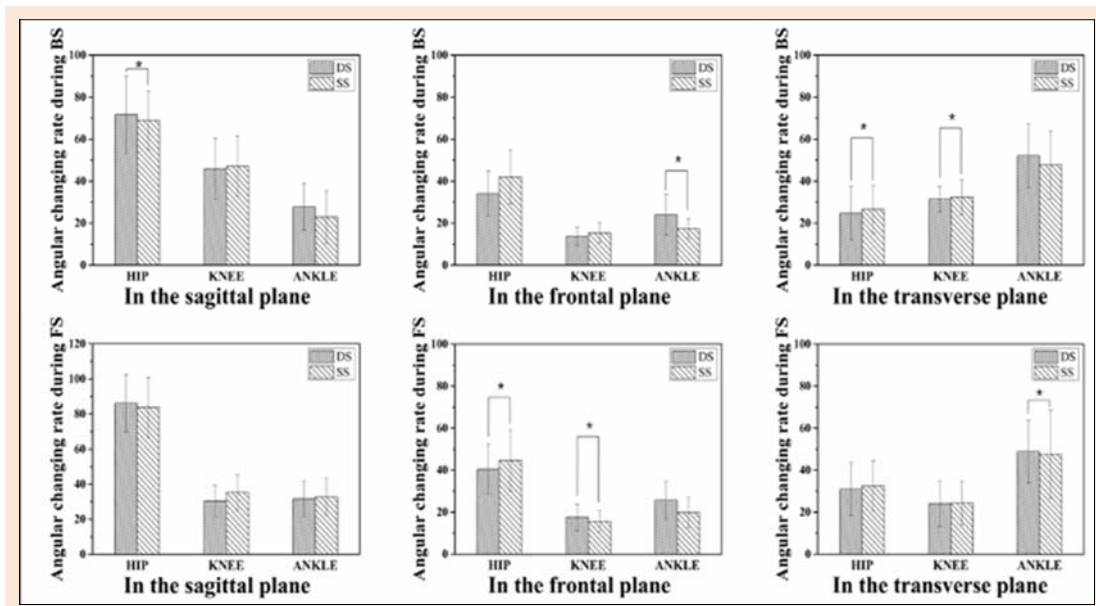


Figure 4. Angular changing rate of lower limb joints during BS and FS in three planes. *indicates a significant difference at the hip, knee, and ankle (respectively) ($p < 0.05$).

Table 4. Comparison of the angular changing rate at the phase of BS and FS between DS and SS (unit: degrees/second). Data are means (\pm SD).

Variables	ANKLE		KNEE		HIP	
	BS	FS	BS	FS	BS	FS
X(DS)	27.8 \pm 11.3	31.7 \pm 10.1	46.0 \pm 14.4	30.4 \pm 8.9	71.7 \pm 18.3*	86.2 \pm 16.3
X(SS)	23.0 \pm 12.6	32.7 \pm 10.7	47.2 \pm 14.3	35.3 \pm 9.9	69.0 \pm 14.0*	84.0 \pm 17.0
Y(DS)	24.0 \pm 9.7*	25.7 \pm 9.0	13.7 \pm 4.3	17.5 \pm 6.4*	34.2 \pm 10.6	40.5 \pm 11.9*
Y(SS)	17.4 \pm 4.8*	19.8 \pm 7.2	15.4 \pm 4.7	15.6 \pm 5.1*	42.1 \pm 12.8	44.6 \pm 14.5*
Z(DS)	52.2 \pm 15.2	48.8 \pm 14.8*	31.4 \pm 6.0*	24.0 \pm 10.8	24.7 \pm 12.8*	31.0 \pm 12.6
Z(SS)	47.7 \pm 16.2	47.7 \pm 21.0*	32.4 \pm 8.4*	24.3 \pm 10.3	26.7 \pm 11.3*	32.5 \pm 11.9

x—the sagittal plane; y—the frontal plane; z—the transverse plane. BS, backward-swing; FS, forward-swing; DS, diagonal shot; SS, straight shot. *indicates a significant difference at the hip, knee, and ankle (respectively) ($p < 0.05$).

Discussion

The purpose of this study was to compare the kinematic characteristics of the lower limbs between the DS and SS. The main findings of the study were as follows. DS showed a significantly less time-spending compared with SS during both the BS and FS phases. Meanwhile, DS showed significantly larger ankle internal rotation and inversion while smaller knee abduction and external rotation during the BS. DS showed significantly larger knee extension while smaller hip adduction and knee internal rotation compared with SS during the FS. However, SS showed significantly larger ROM of ankle plantar flexion external rotation, and significantly larger ROM of knee extension. Moreover, SS showed significantly larger knee internal rotation compared with DS.

DS showed a significantly greater ROM in dorsiflexion and internal rotation of the ankle joint during the BS phase, with a significantly larger ankle eversion at BE. This means that players who perform DS need to perform more warm-up techniques and prepare themselves earlier. Meanwhile, DS has a longer path of movement and the ankle joint seems to absorb more energy, which could help players better adjust for the forward swing action. This is partly consistent with a previous study, Wang et al. (2018) compared the kinematics and electromyographic characteristics during table tennis topspin loop against backspin movement between two different level athletes. Moreover, our findings showed that the motion time of DS was less than SS, which is also an important factor for increasing ball speed (Iino and Kojima, 2009). Malagoli Lanzoni et al. (2018) compared the biomechanical characteristics of cross-court (CC) or long-line (LL) during a table tennis topspin shot. They reported that the lower limb body showed more rotation with respect to the table when playing the LL shot. This finding is supported by this study. Furthermore, no significant difference between shot executions was observed for knee activity on the sagittal plane in this study. This is also consistent with the above study. Therefore, it is speculated that the pelvis and shoulder joints may perform additional compensatory work. In addition, DS showed a significantly greater angular changing rate of ankle eversion and hip flexion, and a significantly larger ankle eversion at BE. Based on the theory of stretch-shortening cycle (Komi and Bosco, 1978; Walshe et al., 1998; Jiang, 2020), the increased ankle eversion and hip flexion may enhance muscle output of the tibialis anterior muscle and gluteus maximus (Zhang et al., 2017), which is a potential factor to increase racket back velocity. This has also been manifested in dissimilar experimental set-ups (Finni et al., 2003; Gregor et al., 1988; Komi, 2000; Stevens, 1993). Meanwhile, Abrams et al. (2012) reported the occurrence rate and prevalence of injuries in tennis athletes. The general tendency was that acute injuries were more common in the lower extremities, while chronic and over-use injuries were more familiar in extremities and trunk of the upper body. The constructed ratio proposed by Croisier and Crielaard (2000) combines two extremely different velocities. Hamstring strains usually occur during joint movements at high speeds. Hewett et al. (2005) measured the neuromuscular control of kinematics and joint loads of

205 female athletes (9 athletes suffered ACL injuries) in high-risk sports such as volleyball, football, and basketball. Compared with the healthy athletes, the knee abduction angle was enhanced when the side-bending athletes landed. The movement, strength, and torque of injured athletes enhanced more rapidly than that of healthy athletes. This could mean that, compared with the SS, the athletes have a higher risk of knee and ankle injuries during the DS.

SS show significantly larger knee joint external rotation and adduction at BE, and significantly larger angular changing rate of knee external rotation in the backward swing phase. This may contribute to the stretching of the internal rotator, resulting in enhanced contraction effects during the forward swing (Zhang et al., 2017). The significantly larger ROM of knee extension with larger ankle external rotation of SS at the forward swing phase may contribute to greater weight transfer range to facilitate momentum generation (Ball and Best, 2007; Zhang et al., 2017). In addition, compared with SS, the movement of hip and ankle joints during the DS was larger. Similarly, the movement of the knee joint of SS is larger than DS. This may mean that players should prepare for a more high-intensity activity for short periods during DS. The knee external rotation and internal rotation of SS was larger than that of DS at BE and FE, respectively, which may result in knee injury, such as anterior cruciate ligament rupture. The ability of the knee joint to remain stable when subjected to the rapidly changing loads during activity relates to dynamic knee stability (Williams et al., 2001). The musculature surrounding the knee is critical for maintaining joint stability (Sanna and Connor, 2008), so we speculate strengthening the muscles around the knee joint can improve the dynamic stability of the knee joint and reduce the risk of a knee injury. Zhang et al. (2017) observed similar results, and suggested that it was beneficial for table tennis players to be able to enhance the speed of wielding the racket in less time for hard shots, because a limited time is allowed to execute a stroke in table tennis. The ability to accelerate the racket in less time in the topspin forehand may be an important factor that affects performance levels during the game. The elite players tended to require less time to enhance the speed of wielding the racket and the contribution of lower trunk axial rotation was significantly smaller for the intermediate players.

Some limitations of this study must be mentioned. The differences in the biomechanical characteristics between bilateral lower limbs were not compared in the study. In addition, information about the variables considered during the racket-ball impact was not included in this study. Kinematics and kinetics data of the lower limbs should be measured simultaneously, and the process of racket-ball impact should be considered in future studies.

Conclusion

This study is a systematic quantitative analysis of lower limb kinematics for the forehand loop techniques with different trajectories for elite athletes. It provides a thorough understanding of the lower limb joint movement patterns of elite male table tennis players when using two styles of different forehand loop techniques. It may be beneficial to

advise coaches and players to pay more attention to the role of the ankle joint in the DS technique, and to pay more attention to strengthening the muscles around the knee joint for reducing the risk of knee injury when practicing SS techniques. These differences between the two shot techniques could be used to help coaches and table tennis athletes optimize performance in both training and competition.

Acknowledgments

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Key points

- Diagonal shot (DS) showed significantly larger ankle internal rotation compared with straight shot (SS) during the backward swing.
- SS showed significantly larger knee internal rotation and extension compared with DS during the forward swing (FS).
- SS showed significantly larger ankle plantar flexion and external rotation ROM compared with DS during the FS.

AUTHOR BIOGRAPHY



Yuqi HE

Employment

Faculty of Sports Science, Ningbo University, China

Degree

Phd Student

Research interests

Biomechanics

E-mail: 1811042041@nbu.edu.cn

	<p>Xiang LV Employment Faculty of Sports Science, Ningbo University, China Degree Master student Research interests Biomechanics E-mail: phoenix960809@163.com</p>
	<p>Zhexiao ZHOU Employment Faculty of Sports Science, Ningbo University, China Degree PhD Research interests Strength and conditioning E-mail: zhouzhexiao@nbu.edu.cn</p>
	<p>Dong SUN Employment Faculty of Sports Science, Ningbo University, China Degree PhD Research interests Biomechanics E-mail: nbusundong@aliyun.com</p>
	<p>Julien S. BAKER Employment Department of Sport, and Physical Education, Hong Kong Baptist University, China Degree PhD Research interests Biomechanics and sports medicine E-mail: jsbaker@hkbu.edu.hk</p>
	<p>Yaodong GU Employment Faculty of Sports Science, Ningbo University, China Degree PhD Research interests Biomechanics E-mail: guyaodong@hotmail.com</p>

✉ **Yaodong Gu**
Dean, Professor, Faculty of Sports Science, Ningbo University,
Zhejiang, China. 315211