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Effects of performance level on lower limb kinematics during table tennis forehand loop

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Understanding of biomechanics is important in performance development since each skill has a fundamental mechanical structure. The purpose of this study was to investigate differences in lower limb kinematics during table tennis forehand loop between superior players (SP) and intermediate players (IP). Thirteen male players as superior and thirteen as intermediate participated in this test. A VICON motion analysis system and a Novel Pedar insole plantar pressure measurement system were used to record kinematic and contact area data, respectively. Participants were asked to execute single forehand loop against topspin ball with maximal power. Key findings were that SP showed significantly larger hip flexion and knee external rotation at backward-end and larger hip internal rotation and extension at forward-end compared with IP. Contact areas at both events were larger for SP. In addition, SP showed significantly larger joints angular changing rate during forward swing at the ankle and hip. Results indicated that SP possessed better ability of using lower limb drive in forehand loop.

Key words: *lower limb drive, contact area, stretch-shortening cycle, kinetic chain*

1. Introduction

Among various techniques in table tennis, forehand loop is considered as one of the most frequent and attacking strokes in competitions [22]. As a complex motion, forehand loop stroke requires both joint flexibility and stability to achieve high racket speed and prevent injury. How to coordinate motion pattern to produce more power and better control in forehand loop is one of the most common concerns for table tennis coaches and athletes.

Limited effort has been focused on the biomechanical analyses on forehand loop. Iino and Kojima [12] stated that although skilled level did not affect racket speed at impact significantly, lower trunk axial rotation showed more contribution to the racket speed in advanced players. The same research team also quantified joint forces and torques of the racket arm as well as the amount of mechanical energy generated and transferred in this arm during topspin forehand, revealing that shoulder internal rotation torque exerted by advanced players was significantly larger, which facilitated energy transferring from trunk to upper arm at a higher rate [13]. These findings support the notion that maximal performance requires optimum activation of all the links in kinetic chain [16]. However, these researches all going in the same direction of biomechanics on upper limb or trunk neglect the lower limb function.

It has been documented that energy generated at lower limb can be transferred to shoulder and upper limb through sequential movements of body segments [4]. Therefore, as the origin of kinetic chain, lower limb drive considerably influences racket and ball speed [4], [10], [21]. Without optimal assistance of lower limb drive, especially the movements of knee joint in the sagittal plane, ball speed is likely decreased in tennis serve [9], [20]. Girard et al. [9] reported that regardless of performance level, ball speed

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showed to be higher with normal knee flexion-extension motion compared with the condition of knee restricted. Research of Reid et al. [20] also highlighted the effect of leg drive with increased mean extension range and peak angular velocity of the rear knee. These outcomes reinforce the view that lower limbs require appropriate degree of knee flexion during backswing to generate greater amount of linear and angular momentum to transfer to the trunk as knee extension [1], [6]. In addition, acting as the linkage of leg and trunk, the motion of hip joint is also vital to energy generation and transference in kinetic chain. Iino and Kojima et al. [14] reported that hip moment was the main contributing factor to trunk rotation in tennis forehand stroke. From a kinematic perspective, Seeley et al. [21] found that hip and ankle motion were also important in lower limb drive. Data of their research suggested that to achieve higher post-impact ball speed players showed increased peak angular velocity of the hip and ankle.

Table tennis demands elaborate movements of upper limb to manipulate racket angle; consequently, the importance of a stable and forceful lower limb base is beyond doubt. Even though insufficient energy generated and transferred from lower limb may be compensated at upper limb, the accuracy and quality of strokes is likely to reduce. To date, there is no systematic study attempting to explore the lower limb biomechanics of the fundamental technique of forehand loop in table tennis. Knowledge of performance level effect on lower limb movement pattern will provide substantial information on how to improve technical movements effectively. Coaches and players need to understand the basic biomechanical principles and how to apply them to the different components or phases of strokes. The purpose of this study, therefore, was to identify the differences in lower limb kinematics while performing forehand loop against topspin balls between superior players (SP) and intermediate players (IP). We hypothesized that SP would show different joint angles from IP at key technique events with different joints range of motion (ROM) during the entire motion phase; SP would also show larger joints angular changing rate during forward swing than IP.

2. Material and methods

Subjects

Twenty-six professional male players from Ningbo University table tennis team volunteered to participate in this test. Thirteen of them are the National Division I players (age: 20.1 ± 0.9 years; height: 174.8 ± 2.5 cm; body mass: 66.9 ± 5.1 kg; training experience: 13.4 ± 1.2 years) categorized as the superior group, and the rest are the National Division II players (age: 21.2 ± 1.6 years; height: 175.2 ± 2.4 cm; body mass: 69.1 ± 4.1 kg; training experience: 10.2 ± 1.9 years) categorized as the intermediate group. All participants were right-handed style with no previous lower extremity and foot diseases or deformity, and were free from injury for at least six months prior to the test. All subjects provided informed consent for participation in this test, which was approved by the Human Ethics Committee of Ningbo University.

Data collection

Tests took place in Ningbo University table tennis training gymnasium. The floor is made of wood which is commonly used in daily training and competitions. A ball machine placed 1.2 m away from the opponent's court was used to project topspin balls directly to the foreside of the subjects' court. Settings including projecting angle, radian, velocity and frequency were consistent for all balls. All subjects were informed of the test procedures and dropping position and spin direction of the balls. Sufficient time was also given for them to warm up and familiarize themselves with the experimental environment. Since they were proficient in forehand loop technique, only a brief instruction was set out to ensure the motion quality. During testing, subjects were asked to perform single crosscourt forehand loop in situ (Fig. 1) with full effort wearing the unified training footwear. A 8-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data at a frequency of 200 Hz. 16 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. A Novel Pedar insole plantar pressure measurement system (Novel GmbH, Munich, Germany) was used to record data of contact area at 50 Hz. Kinematic and kinetic testing were conducted synchronously. At least five successful attempts were performed for one subject. Smoothness of the motion was judged by players themselves and the quality of the balls' effect was supervised by their coaches. In addition, it is imperative to note that data were collected separately for the five attempts to distinguish with consecutive strokes.

(a) Neutral position (NP) (b) Backward-end (BE) (c) Forward-end (FE)

Fig. 1. Three key events during one forehand loop motion

Data processing

This study divided the entire forehand loop motion into two phases of backswing and forward-swing. Backswing phase referred to the period between two certain events of neutral position (NP) and backward-end (BE, maximum knee flexion) and forward swing phase referred to the period between events of BE and forward-end (FE, maximum hip internal rotation) (Fig. 1). Joint angles in three planes were time-normalized to 100 data points. Variables of the dominant side as joint angles at BE and FE, joints range of motion (ROM) and joints angular changing rate during forward swing (R_f) in three planes were processed for analysis. To gain a further insight into the ankle motion, this study also measured plantar contact area. The plantar was divided into six regions as big toe (BT), other toes (OT), medial forefoot (MF), lateral forefoot (LF), midfoot (M) and rearfoot (R). Variables of contact area under each region at BE and FE were also compared between IP and SP.

Statistical analysis

All statistical analyses were conducted using Stata 12.0 (Stata Corp, College station, TX). Initial Shapiro–Wilk tests validated that the data were normally distributed. To examine the differences between two performance levels, independent *t*-test was taken for each variable including the time of entire motion, joint angles at BE and FE, joints ROM, R_f and contact areas. Statistical results were considered significant if $p < 0.05$.

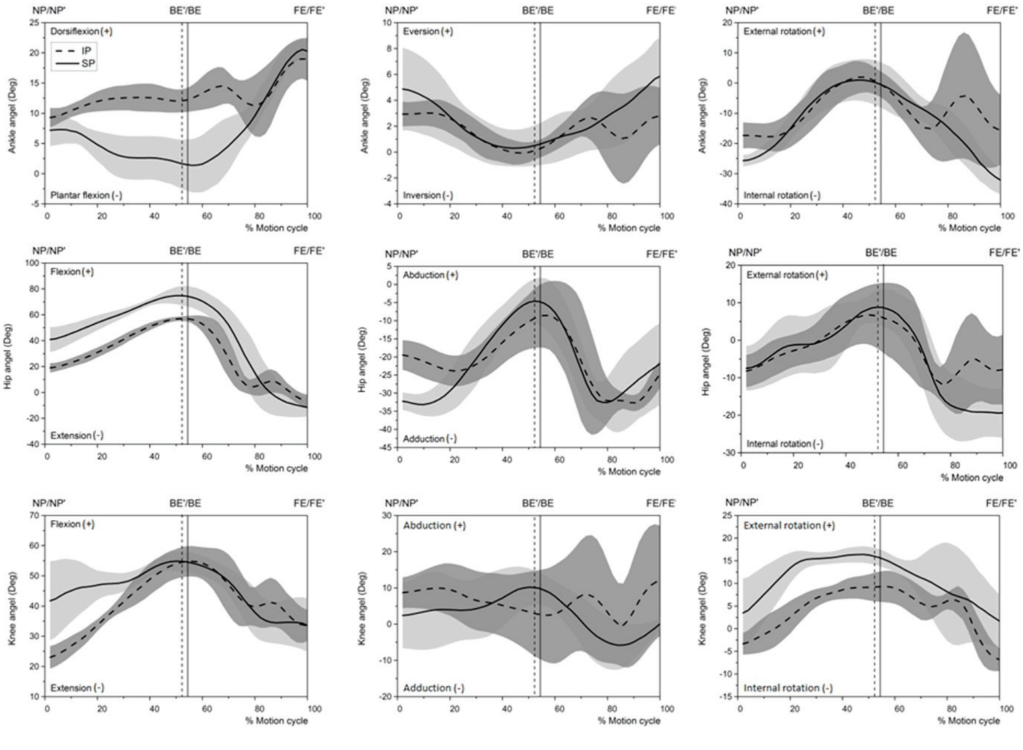

Fig. 2. Changes of lower limb joints (Top: ankle; Middle: hip; Bottom: knee) during one motion cycle in three planes (Left: in the sagittal plane; Middle: in the frontal plane; Right: in the transverse plane). NP/NP'; moment of neutral position for SP and IP, respectively; BE'/BE, moment of backward-end for IP and SP, respectively; FE/FE', moment of forward-end for SP and IP, respectively)

3. Results

The time to perform one forehand loop was 0.87 ± 0.06 s and 1.04 ± 0.09 s for SP and IP, respectively, with significance. Changes of joint angles during one motion cycle in the sagittal, frontal and transverse planes for both IP and SP were generally comparable (Fig. 2). Joint angles almost peak at the moment of motion transition between backswing and forward swing (Fig. 2). Significant differences in joint angles at key events between IP and SP were found in the sagittal and transverse planes (Table 1). Compared with IP, SP showed significantly smaller ankle dorsiflexion with larger hip flexion and knee external rotation at BE and significantly larger ankle internal rotation, hip extension and internal rotation with smaller knee internal rotation at FE. In the frontal plane, there was no significant difference between performance levels at each event. Joints ROM during one entire motion also showed significant differences between IP and SP (Table 2). For SP, ROM of the ankle in the sagittal plane and that of the hip in the sagittal and transverse planes showed to be significantly larger, while the knee ROM in the sagittal plane was significantly smaller than IP.

Table 1. Comparison of joint angles at key events in three planes between IP and SP, mean ± SD

Event		Ankle		Hip		Knee	
		IP	SP	IP	SP	IP	SP
BE	*x*	12.1 ± 1.9	1.4 ± 4.3*	57.1 ± 1.8	74.2 ± 8.1**	54.7 ± 5.0	54.5 ± 3.6
	y	0.2 ± 0.7	0.6 ± 1.6	–9.0 ± 8.4	–4.8 ± 6.7	2.8 ± 12.0	9.8 ± 4.4
	z	0.3 ± 4.3	–0.7 ± 7.5	6.4 ± 8.9	8.7 ± 5.3	9.2 ± 3.3	15.6 ± 1. 9***
FE	*x*	17. 9 ± 4.3	18.8 ± 2.1	–5.6 ± 3.3	–12.8 ± 5.1**	34.8 ± 4.1	32.1 ± 9.1
	y	2.7 ± 2.0	5.8 ± 2.9	–21.2 ± 3.9	–20.5 ± 10.8	11.6 ± 13.2	1.9 ± 1.7
	z	–15.1 ± 10.7	–33.1 ± 4.6*	–7.2 ± 9.9	–19.1 ± 7.6**	–7.0 ± 1.2	0.9 ± 5.4***

Note: *x* – the sagittal plane; *y* – the frontal plane; *z* – the transverse plane.
* $P < .05$, significant difference at the ankle.
** $P < .05$, significant difference at the hip.
*** $P < .05$, significant difference at the knee.

Table 2. Joints ROM of the entire motion of IP and SP, mean ± SD

	Ankle		Hip		Knee	
	IP	SP	IP	SP	IP	SP
x	11.7 ± 3.2	20.4 ± 4.1*	65.5 ± 3.0	89.4 ± 3.8**	33.7 ± 4.4	25.5 ± 6.3***
y	4.7 ± 0.5	5.8 ± 2.0	28.0 ± 4.9	32.1 ± 4.5	20.6 ± 3.8	18.0 ± 3.8
z	29.5 ± 3.8	35.1 ± 9.9	23.5 ± 1.2	31.9 ± 6.6**	18.5 ± 2.1	18.3 ± 4.1

Note: *x* – the sagittal plane; *y* – the frontal plane; *z* – the transverse plane.
* $P < .05$, significant difference at the ankle.
** $P < .05$, significant difference at the hip.
*** $P < .05$, significant difference at the knee.

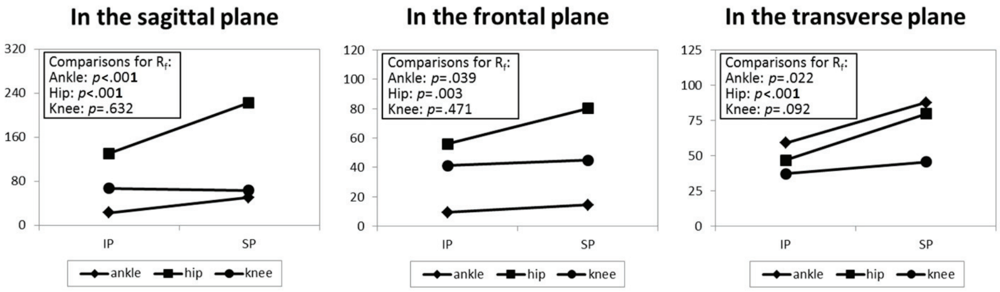

Fig. 3. Angular changing rate of lower limb joints during forward-swing phase in three planes

Table 3. Contact area (cm^2) of each plantar region at BE and FE, mean ± SD

		BT 	OT 	MF 	LF 	M. 	R 
BE	SP	5.6 ± 0.8	10.3 ± 3.1*	10.1 ± 1. 7	23.7 ± 0.4	29.5 ± 1.2*	33.8 ± 1.2*
	IP	5.8 ± 0.6	16.0 ± 1. 8	10.5 ± 2.8	23. 5 ± 0.9	21.7 ± 3.2	28.9 ± 2.8
FE	SP	7.3 ± 0.8*	13.1 ± 2.2	16.2 ± 0.7*	11.6 ± 2.0*	0.8 ± 1.3*	2.9 ± 2.4*
	IP	7.6 ± 0.4	15.2 ± 1.8	10.8 ± 2.1	7.1 ± 1.3	0.1 ± 0.4	0.4 ± 0.7

Note: * $P < .05$, significant difference.

Concerning joints R_f, in the sagittal plane, R_f at the ankle and hip for SP was clearly larger than that of IP, while R_f at the knee was slightly smaller for SP. In the frontal and transverse planes, R_f of all joints showed to be larger for SP. Differences only in the ankle and hip reached to statistical significance (Fig. 3).

In general, SP showed larger contact area than IP (Table 3). For SP, regions of M and R were significantly larger while OT was smaller at BE. At the event of FE, SP exhibited obviously larger contact area with significance under plantar regions of MF, LF, M and R than IP. While the region of BT was shown to be significantly smaller for SP at FE, but this difference was very subtle.

4. Discussion

A thorough understanding of lower limb joints movement pattern of players with different skilled levels has important implications on sports performance enhancement and injury prevention. This study investigated differences in lower limb kinematics during forehand loop against topspin ball between superior (SP) and intermediate players (IP). Key phases (backward swing and forward swing) and technique events (backward-end, BE and forward-end, FE) were identified for in-depth analysis. Our findings suggested that SP could complete one forehand loop within less time than IP. In table tennis games, SP execute a stroke in less time so that they can have enough time to move to an appropriate position with stable footwork for the next stroke. Moreover, for SP, forward swing phase accounted for less time in an entire motion cycle. The ability to accelerate the racket rapidly during forward swing of forehand loop may be an important factor for increasing ball speed [12]. Significant differences in kinematics were found in ankle dorsiflexion, hip flexion, knee external rotation at BE and ankle plantar flexion, hip extension, knee rotation at FE. In addition, joints angular changing rate of ankle and hip angles during forward swing increased significantly in three planes for SP compared with IP. With respect to joints ROM of the entire motion, significant differences were observed in all three joints in the sagittal plane and in the hip in the transverse plane.

During backswing, ankle movement of SP progressed to obvious plantar flexion, in contrast, that of IP progressed to dorsiflexion. As a result, IP exhibited significantly larger ankle dorsiflexion than SP at the completion of this period. This was in line with the results of plantar contact area that IP showed significantly larger contact area at OT region and significantly smaller area at M and R regions at BE, indicating that IP distributed more body weight on the forepart of the plantar while SP were able to distribute body weight more evenly on the full plantar at this moment. The larger contact area of SP provided a more stable base for performing the following motion of forward swing. At the event of BE, SP also showed significantly larger hip flexion compared with IP. Based on the theory of stretch-shortening cycle that the utilization of elastic energy stored in muscle-tendon complex during the eccentric phase (stretch) could partially enhance the concentric performance (shorten) [4], [17], [23], it can be inferred that the increased hip flexion of SP at BE may enhance muscle output of gluteus maximus during forward swing, which is a potential factor to increase racket velocity in the kinetic chain. Seeley et al. [21] revealed that in tennis forehand stroke the peak joint angles of hip flexion, knee flexion and ankle dorsiflexion prior to ball impact increased as post-impact ball speed increased. For the same reason, the significantly larger knee external rotation of SP at the event of BE may contribute to stretching the internal rotator, resulting in enhanced contraction effect during forward swing. Previous study demonstrated that the rise of body centre of gravity was lowest in squatting jump which had no appreciable elastic energy storage in starting position compared with counter-movement jump and drop jump [17]. Similarly, increasing the maximal external rotation during backswing could effectively improve velocity of tennis serve [7]. Myers et al. [19] reported that increased rotational countermovement of torso and pelvic at the top of downswing in golf was associated with increased ball velocity.

During forward swing, lower limb movements of SP were slightly different from that of IP. At the event of FE, although ankle angles showed no significant difference in the sagittal plane, contact area of SP under MF, LF, M and R regions increased significantly while the BT region showed significant but less decrease, indicating that IP presented more apparent "heel-off" at the completion of the motion. For SP, larger contact area at this moment may benefit for recovering to the neutral position to prepare for the next stroke. With greater ankle rotation ROM in the entire motion, SP showed more flexible ankle motion, however, the significantly larger internal rotation at the event of FE may put SP at potential risk of ankle sprain [8], [18]. Significant difference in the knee angle at the event of FE was also observed in the transverse plane. Compared with IP, SP showed less internal rotation at this moment. Although this study did not quantify the amount of knee rotation during forward swing, the idea that the IP possessed comparable knee mobility in the transverse plane with SP in lower limb drive can be concluded when synthesizing the observations at both events of BE and FE. Additionally, IP showed greater knee ROM in the sagittal plane, which was mainly due to the less flexion at the event of NP. This may suggest a more stable centre of mass shift for SP during backswing. As to the hip, the larger ROM in the sagittal plane of SP was attributed to more flexion at BE with more extension at FE. Similarly, the larger ROM in the transverse plane was mainly due to larger internal rotation at FE. The greater hip motion range was likely to be associated with larger weight transfer range which could facilitate momentum generation [2].

The more important factor related to optimizing energy transfer in kinetic chain is joint angular velocity which is expected to increase as skilled level improves [21]. The present study compared differences in angular changing rate of lower limb joints during forward swing (R_f) between SP and IP. Significant differences were found in the ankle and hip. Compared with IP, SP showed more effective lower limb drive with obviously larger R_f of the ankle and hip in three planes. Although the study of Seeley et al. [21] did not differentiate skilled level of subjects, it revealed that peak hip extension and ankle plantar flexion velocity increased as post-impact ball speed increased from slow to medium level. The increased ankle and hip R_f of SP in this study may be related to more effective lower limb drive to increase ball speed. In fact, all links in the kinetic chain must coordinate only in such a way that a high racquet speed can be generated at impact without undue risk of injury [3], [4]. Kibler [15] calculated that 51% of total energy and 54% of total force were developed in the leg-hip-trunk link during tennis activities. Dysfunction of any segment in the chain will lead to an increased reliance on the others to accommodate this loss. Elliot et al. [5] reported that tennis players with less knee flexion during backswing exhibited higher loading at shoulder and elbow in the service action. Although the importance of knee motion in lower limb drive has been emphasized repeatedly in studies on tennis serve or forehand strokes, no significant differences were found in R_f of the knee in the present study. This contradiction may be due to that subjects recruited in this study were all skilled players with at least eight-year training experience; as a result, both IP and SP showed comparable lower limb drive effect at the knee.

However, there are some limitations in this study. First, the subjects participated in were recruited from a collegiate table tennis team for each performance level. Although they were respectively granted with National Division I and National Division II, the skill gap between them was not highly distinct, which might moderate the significance of some variables. Second, we only compared differences of the dominant limb kinematics; in fact, the non-dominant limb also plays an important role in stabilizing body balance especially during the deceleration stage in forward swing. Third, the experiment was performed under specialized training condition instead of real competitions, considering various uncontrollable factors in competitions that would affect motion repeatability such as psychology and unfixed drop points of balls, etc.

This study probed into the effect of performance level on lower limb kinematics during table tennis forehand loop. The present outcomes confirmed that superior players possessed better ability of using lower limb drive in this technique. Generally, superior players performed the forehand loop within less time. In addition, superior players showed relatively sufficient hip and knee motion during backswing, which is a possible strategy to utilize elastic energy. Ankle and hip angular velocity changing rate during forward swing of superior players were significantly higher, which may contribute to momentum generation and transference from the lower limb to the trunk and upper limbs. In conclusion, although the role of knee motion in lower limb drive was not significant between intermediate and superior levels, training on improving the dominant ankle and hip flexibility including enlarging flexion during backswing and increasing dorsiflexion/extension and rotation velocity during forward swing are important for forehand loop technique enhancement for intermediate players.

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