Analysis of Mechanical Loads on Lower-Extremity Joints During Chassé-Step Footwork in Elite Table Tennis Athletes

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Abstract

Objective: Innovations in table tennis competition rules and the rapid development of playing styles and shot placement have imposed higher demands on athletes' comprehensive technical abilities. Gradually increasing exercise intensity and inappropriate technical movements may increase the risk of injury and affect athletic performance. This study aimed to analyze the biomechanical loading characteristics of lower-limb joints during the side-step footwork of high-level table tennis players of different sexes, providing a theoretical reference for injury prevention and control in table tennis athletes. Methods: Biomechanical data, including reflective marker trajectories, ground reaction forces, and surface electromyography, were collected from 18 male and 18 female national first-class table tennis players performing side-step footwork. OpenSim musculoskeletal modeling and simulation were used to calculate lower-limb joint contact forces in table tennis players, and model validation was completed. Results: Comparison between the simulated muscle activation and the amplitudes of surface electromyographic signals validated the muscle activation, muscle force, and related data obtained using OpenSim. Males exhibited greater hip joint contact forces in the anterior-posterior and medial-lateral directions during the racket-swing phase, whereas females exhibited greater knee joint contact forces in the vertical direction. Conclusion: High-level male table tennis players demonstrated faster hip joint force output during side-step footwork, which may help increase racket-swing and ball-striking speed. Female athletes should enhance knee joint stability and strength training to avoid excessive knee joint loading and prevent related injury risks. In addition, based on experimentally driven OpenSim modeling and simulation, this study analyzed and verified the reliability of its application in calculating biomechanical loading parameters of fundamental table tennis footwork, and it may be applied in future musculoskeletal modeling and simulation studies of various table tennis technical movements.

Full Text

Analysis of Mechanical Loads on Lower-Extremity Joints During Chassé-Step Footwork in Elite Table Tennis Athletes

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Abstract: Objective The innovation of table tennis competition rules and the rapid development of playing styles and shot routes have imposed higher demands on athletes' comprehensive technical abilities. The progressively increasing exercise intensity and inappropriate technical movements may increase the risk of injury and affect athletic performance. This study aimed to analyze the characteristics of lower-extremity joint biomechanical loading during chassé-step footwork in elite table tennis athletes of different sexes, providing a theoretical reference for injury prevention and treatment in table tennis athletes. **Methods** Biomechanical data—including reflective-marker trajectories, ground reaction forces, and surface electromyography—were collected from 18 male and 18 female national first-class table tennis athletes while performing chassé-step footwork. OpenSim musculoskeletal modeling and simulation were used to calculate lower-extremity joint contact forces in table tennis athletes, and model validation was completed. **Results** Comparison between the simulated muscle activations and the amplitudes of surface electromyographic signals validated the muscle activation, muscle force, and related data obtained from OpenSim calculations. In males, the hip joint showed larger joint contact forces in the anteroposterior and mediolateral directions during the swing phase, whereas in females, the knee joint showed larger joint contact forces in the vertical direction. **Conclusion** Elite male table tennis athletes exhibited faster hip-joint force output during chassé-step footwork, which helps increase racket-swing and ball-striking speed. Female athletes should enhance knee-joint stability and strength training to avoid excessive knee-joint loading and prevent related injury risks. In addition, based on experimental-data-driven OpenSim modeling and simulation, this study analyzed and verified the reliability of its application in calculating biomechanical loading parameters of basic table tennis footwork. In the future, it may be applied to musculoskeletal modeling and simulation studies of various table tennis technical movements.

Keywords: biomechanics; table tennis; technical footwork; injury mechanism

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Analysis of mechanical loadings in the lower extremity during chasse step footwork of elite table tennis athletes

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…techniques place higher demands on athletes' skills. Greater intensity and incorrect technique may increase the probability of sports injuries. This study aims to analyze sex differences in the biomechanical characteristics of the lower-limb joints of elite table tennis athletes during the chassé step, thereby providing a theoretical reference for injury prevention and treatment in table tennis athletes. **Method** Biomechanical data—including marker trajectories, ground reaction forces, and EMG signals—were collected from 18 male and 18 female National Class-I table tennis athletes. The OpenSim musculoskeletal modeling platform was used to calculate lower-limb joint contact forces in table tennis athletes, and model validation was completed. **Results** Muscle activation and muscle force estimated by OpenSim were validated by comparing simulated muscle activation with surface EMG signals. Hip-joint contact forces in males were greater in the anterior–posterior and medial–lateral directions, whereas females showed greater knee-joint contact force in the superior–inferior direction. **Conclusion** Elite male table tennis athletes exhibited greater hip-joint force during the chassé step, which may improve racket swing speed; female athletes need to train knee stability and the relevant muscles to avoid excessive knee loading and thereby prevent potential injuries. In addition, this study verified an experimental-data-driven OpenSim simulation and validated the reliability of its application in calculating biomechanical loads during typical table tennis footwork, which can be used in future research on musculoskeletal modeling of different table tennis movements.

Key words: biomechanics; table tennis; technical footwork; injury mechanism

Fundamental technical movements are among the key factors affecting the athletic performance of table tennis players[1]. Establishing a rigorous and distinctive technical training system helps promote technical breakthroughs among table tennis athletes. A technical system generally includes footwork (chassé step, single step, cross step), strokes (serve, forehand, backhand), and so forth. Among these, as a basic component of the technical system, footwork is an indispensable carrier in the stroke process[2–4]. As a complex net-separated adversarial sport, table tennis involves an extremely short hitting time: not only is the ball very fast, but the distance within which the athlete can adjust is also very limited. During the brief hitting process, table tennis athletes must analyze and decide how to return the ball, and move to a reasonable position to complete the stroke[2,5]. To reach a higher level, table tennis athletes need to undertake large amounts of high-intensity training; however, excessive sports training may lead to injuries in different body regions. Therefore, scientific analysis of the technical footwork of table tennis athletes can help coaches and athletes identify the key factors in table tennis technical footwork, optimize technical footwork training, and reduce the risk of related sports injuries[6].

Research on lower-limb biomechanics is crucial for revealing how, during training and competition, improper technical movements in table tennis athletes alter kinematic performance and kinetic loads, thereby aggravating joint loading associated with potential injury risk[7]. The geometric structure and lines of action of the human musculoskeletal system are highly important for neuromuscular control function, because they determine the moment arms of the relevant muscle groups and regulate muscle force and joint moments. Since muscle force output depends on changes in muscle–tendon length, an accurate musculoskeletal geometric specification can precisely calculate muscle–tendon forces and loads such as joint contact forces[8–9]. The OpenSim musculoskeletal modeling and simulation platform can construct core computational components and also provides open-source access to control algorithms, analysis tools, and other functions[10–11], enabling calculation of biomechanical loading indicators such as joint moments and joint contact forces. In this study, athletes of different sexes were analyzed through OpenSim musculoskeletal modeling to calculate load characteristics, including lower-limb joint contact forces and muscle activation, during the chassé-step technique of high-level table tennis athletes (one of the most common technical footwork patterns in table tennis[12]). The aim was to provide practical insights and theoretical references for scientific training of high-level table tennis athletes, for reducing the risk of injuries related to lower-limb joints and muscles, and for clarifying potential injury mechanisms.

1 Research Methods

1.1 Participants

Thirty-six National Class-I table tennis athletes were recruited, all of whom habitually held the racket with the right hand. Among them, there were 18 males, aged 21 ± 1.34 years, with height 175 ± 5.54 cm and body mass 74 ± 2.79 kg; and 18 females, aged 20 ± 0.71 years, with height 164 ± 1.00 cm and body mass 54 ± 4.92 kg. Strict medical screening was conducted before the experiment to ensure that the selected participants were in good physical condition and had no sports injuries to the lower-limb muscles, joints, or related structures within the 6 months before the experiment. Before the experimental testing, the participants were clearly informed of the experimental requirements and specific procedures, and signed the relevant informed-consent form.

1.2 Experimental Testing Procedure

The experiment used an eight-camera Vicon three-dimensional infrared motion-capture sys-

system (VICON, Oxford, England) was used to collect kinematic trajectory data from the table-tennis athletes' reflective marker points, with the sampling frequency set at 200 Hz; a synchronized three-dimensional force platform (AMTI, Watertown, USA) recorded ground reaction force data during the athletes' footwork movements at a frequency of 1,000 Hz; and a synchronized Delsys surface electromyography testing system (Delsys, Boston, MA, United States) collected surface electromyography signals (sEMG) from seven specific lower-limb muscles at a frequency of 2,000 Hz.

In the experimental test, a 52-marker model using Marker points (diameter: 14 mm) was adopted (Fig. 1). The markers were attached to the left and right upper and lower limbs. Specific locations included the shoulder joint, distal humeral joint, distal radial and ulnar joints, proximal joints of the second and fifth phalanges, anterior superior iliac spine, posterior superior iliac spine, distal femur, distal tibia, distal fibula, proximal and distal joints of the heads of the first and fifth metatarsals, distal joint of the first phalanx, the midpoint between the distal joints of the second and third phalanges and the calcaneus, as well as four-marker tracking clusters attached to the upper arm, forearm, thigh, and shank. Surface electrodes were attached to the right lower limb (Fig. 1), including the tibialis anterior (TA), medial gastrocnemius (GM), lateral gastrocnemius (GL), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and lateral biceps femoris (BL).

After the athletes had fully familiarized themselves with the experimental environment, the skin was wiped with alcohol, and the surface electrodes were placed over the muscle belly of the corresponding muscles, parallel to the longitudinal axis of muscle contraction. To record the maximum value of muscle activity, the athletes were required to perform two maximum voluntary contraction (MVC) tests, which were used for subsequent calculation of the root mean square (RMS) values of the maximum activation level. During the experiment, the motion-capture system synchronously collected one set of static marker-position data and ground reaction force data; synchronized ball-striking and footwork movement tests were then conducted, and five successful dynamic footwork trials were collected and recorded for each athlete.

Fig. 1 Schematic illustration of the musculoskeletal model and surface electromyography

Fig. 1 Illustration of subject-specific modelling and surface EMG measurement

Figure labels visible in Fig. 1 include: Marker; Vicon; OpenSim; Delsys; rectus femoris; vastus lateralis; vastus medialis; tibialis anterior; lateral biceps femoris; lateral gastrocnemius; medial gastrocnemius; superior-inferior direction; medial-lateral direction; anterior-posterior direction.

1. First receiving area; 2. Second receiving area; 3. Target hitting area.

Fig. 2 Schematic illustration of the experimental design

Fig. 2 Illustration of experimental set-up

Figure labels visible in Fig. 2 include: coach; force platform; camera; athlete; table-tennis ball.

The laboratory environment simulated the competition venue. A competition-specific table-tennis table (Rainbow series, Double Happiness Sports Co., Shanghai, China) and table-tennis balls (D40+, Double Happiness, Shanghai, China) were used. The table area consisted of two receiving areas and one target hitting area (20 cm × 20 cm). In the formal experiment, all athletes first performed 5 min of multiball training using the side-step footwork. Subsequently, a professional coach served the ball, and the athlete struck a forehand topspin from the first receiving area (area 1 in Fig. 2, black footprints) to the target hitting area (area 3 in Fig. 2). The athlete then used side-step footwork—that is, the left lower limb moved toward the right lower limb, and the right lower limb moved to the right side—to prepare for the second forehand topspin stroke (area 2 in Fig. 2, blue footprints). A trial was considered valid when the athlete hit the ball into the target hitting area (area 3 in Fig. 2).

1.3 Division of Movement Phases

The movement phases were mainly divided into the ready position, backswing phase, swing phase, and recovery phase. In the side-step footwork, when the athlete stepped from the ready position (Fig. 3a) onto the force platform (the vertical ground reaction force of the force platform changed from absent to present), the movement entered the backswing phase (Fig. 3b) and reached the end of the backswing (Fig. 3c, 0–30%). This was followed by the swing phase (Fig. 3d) until the end of the swing (Fig. 3e; 31%–55% for females and 31%–60% for males). After pushing off from the force platform (the vertical ground reaction force of the force platform changed from present to absent), the athlete returned to the ready position (Fig. 3a) through the recovery phase (Fig. 3e).

(a) Ready position (b) Backswing phase (c) End of backswing (d) Swing phase (e) End of swing

Fig. 3 Division of movement phases

Fig. 3 The division of stance

1.4 Model establishment and data processing

The C3D data collected by the motion-capture system were directly imported into MATLAB, and the coordinate axes were transformed and filtered using the `c3dExport.m` program. An OpenSim (v4.2) musculoskeletal model was adopted, and the data were processed according to the standard workflow

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. First, scaling was performed according to each athlete' s static marker positions to obtain an individualized model accurately matched to the measured parameters. To reduce errors, inverse kinematics (IK) with weighted markers was used to calculate joint angles. Subsequently, inverse dynamics (ID) was performed using the joint angles and ground reaction forces to calculate joint moments. The static optimization algorithm (`static opensim`, SO) was used to analyze lower-limb muscle activation and muscle forces; the muscle activation was then compared with the muscle activity in the electromyographic signals to validate the musculoskeletal model used in this study. Finally, the validated muscle-force data were loaded into the analysis tool (`analysis`) to calculate the joint reaction forces of the lower-limb joints, namely the joint contact forces. Surface electromyographic signals were filtered using root-mean-square band-pass filtering (10–500 Hz, FFT filter) to calculate the peak EMG amplitudes of male and female table tennis players during the chasse-step. The mean EMG amplitude of each muscle during the chasse-step was used for analysis.

In the Delsys EMG working software, MVC and the chasse-step experiment were calculated using the root mean square (RMS):

$$\text{RMS} = \left(\frac{1}{s} \sum^{s} f^2(s) \right)^{\frac{1}{2}} \tag{1}$$

where s is the window length (points), and $f(s)$ is the data within the window.

In OpenSim, activation is expressed in the range of 0–1, where 0 indicates complete inactivity and 1 indicates the maximum activation level

$$15 - 16$$

. As shown in Formula 2, the EMG signal activation during the chasse-step was normalized to the range of 0–1. The experimental data were compared with the simulation data to validate the model.

$$A_{\text{EMG}} = \frac{R_t}{R_m} \tag{2}$$

where A_{EMG} is the normalized EMG amplitude, and R_m is the RMS amplitude during maximum voluntary contraction (MVC).

1.5 Statistical analysis

The Shapiro–Wilk test was used to determine whether the data indicators conformed to a normal distribution. Joint contact-force indicators during the support phase of the chasse-step were selected and standardized by interpolation to 101 data points. An independent-samples t-test was used to compare and analyze sex differences. Specifically, the open-source one-dimensional statistical parametric mapping method (SPM 1D) was used to perform statistical analysis of lower-limb joint contact forces

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. The relevant data statistics were analyzed using MATLAB R2019a (The MathWorks, MA, United States), with the significance threshold set at 0.05.

2 Results

2.1 Model validation

The activation levels of seven lower-limb muscles in elite male table tennis players during the chasse-step are shown in Fig. 4, including the rectus femoris (RF), biceps femoris lateral head (BF), vastus lateralis (VL), vastus medialis (VM), tibialis anterior (TA), medial gastrocnemius (GM), and lateral gastrocnemius (GL). Comparison of the means and standard deviations showed that the activation levels of the experimentally recorded surface EMG signals of the muscles (RF, VM, VL, BF, GM, GL, TA) were close to the muscle activation levels calculated by OpenSim.

Fig. 4 Comparison of lower-limb muscle activation during the chasse-step in male table tennis players

Fig. 4 Lower limb muscle activation during chasse-step in male table tennis athletes

In addition, during the chasse-step movement phase, the medial gastrocnemius of the lower limbs in male table-tennis athletes showed the greatest activation, followed by the vastus lateralis. The vastus medialis was activated more strongly than the lateral gastrocnemius; activation of the lateral biceps femoris exceeded 60%, while the rectus femoris showed the lowest activation.

2.2 Joint Contact Force

During the chasse-step, the anterior–posterior hip-joint contact force in male athletes was smaller than that in female athletes during the 4%–5% phase ($P = 0.046$); however, in female athletes it was smaller than in male athletes during the 58%–65% phase ($P = 0.005$). In the superior–inferior direction, the hip-joint contact force in male athletes was greater than that in female athletes during 4%-7% of the overall movement phase ($P = 0.0031$). Moreover, the medial-lateral hip-joint contact force during the chasse-step was greater in male athletes than in female athletes during the 8%-10% ($P = 0.0038$), 30%-55% ($P < 0.001$), and 60%-65% ($P = 0.010$) phases; by contrast, female athletes showed greater medial-lateral hip-joint contact force only during 3%-6% of the movement phase ($P = 0.0044$) (Fig. 5).

Fig. 5 Schematic comparison of hip contact forces during the chasse-step between male and female athletes
Fig. 5 Comparison of hip contact forces during chasse-step between male and female athletes

Subpanels:
(a) Hip joint, anterior-posterior direction
(b) Hip joint, superior-inferior direction
(c) Hip joint, medial-lateral direction

During the chasse-step movement phase, there was no significant difference between male and female athletes in the anterior-posterior knee-joint contact force. However, during the 4%-6% phase ($P = 0.041$), the superior-inferior knee-joint contact force during the chasse-step was greater in male athletes than in female athletes. In the superior-inferior direction at 50% ($P = 0.025$), and in the medial-lateral direction during 5%-6% ($P = 0.047$), the knee-joint contact force was greater in female athletes than in male athletes (Fig. 6).

Fig. 6 Schematic comparison of knee contact forces during the chasse-step between male and female athletes
Fig. 6 Comparison of knee contact forces during chasse-step between male and female athletes

Subpanels:
(a) Knee joint, anterior-posterior direction
(b) Knee joint, superior-inferior direction
(c) Knee joint, medial-lateral direction

There was no significant difference between male and female table-tennis athletes in the anterior-posterior ankle-joint contact force. Male athletes showed greater superior-inferior ankle-joint contact force during the chasse-step than female table-tennis athletes during 80%-90% ($P = 0.001$) and 91%-95% ($P = 0.009$). However, in the medial-lateral direction, female athletes showed greater ankle-joint contact force at the beginning of the chasse-step movement, during 0%-1% ($P = 0.050$), and during 92%-96% ($P = 0.028$) (Fig. 7).

Fig. 7 (in-figure labels). Legends: male, female, SD. Axes: joint contact force ($*BW$), movement phase (100%), and $SPM\{t\}$.
(a) Ankle joint, anterior-posterior direction; $\alpha = 0.05$, $t^* = 3.315$.
(b) Ankle joint, superior-inferior direction; $p = 0.009$, $p = 0.001$; $\alpha = 0.05$, $t^* = 3.383$.
(c) Ankle joint, medial-lateral direction; $\alpha = 0.05$, $t^* = 3.384$; $p = 0.028$,

$p = 0.050$.

Figure 7 Schematic comparison of ankle-joint contact forces during the chasse-step between male and female athletes

Fig. 7 Comparison of ankle contact forces during chasse-step between male and female athletes

3 Analysis and Discussion

Footwork technique is one of the fundamental techniques in table tennis and is also an important component of table-tennis training and competition

[18 − 19]

. To strike the ball more effectively, table-tennis athletes need to use appropriate technical footwork to move to the optimal position

[5]

. From a biomechanical perspective, this study mainly investigated, by sex, the characteristics of lower-limb joint contact forces in the chasse-step technique of high-level male and female table-tennis athletes. According to the division of movement phases, from the beginning of the movement to approximately 30% of the support phase corresponds to the end of the backswing; subsequently, from 55% of the support phase in women to 60% in men corresponds to the end of the forward swing. This study found that during the forward-swing phase of the chasse-step, female athletes had greater knee-joint contact force in the superior–inferior direction than male athletes, whereas male athletes had greater hip-joint contact forces in the anterior–posterior and medial–lateral directions during the forward-swing phase. Comparison of athletes' lower-limb surface electromyography signals with the muscle activations calculated by OpenSim was used to validate the model. The activation levels of most muscle groups were similar to the electromyographic data; only the tibialis anterior showed relatively large variation, the potential reason for which may be related to active ankle dorsiflexion during push-off.

The muscle activation levels calculated by OpenSim static-optimization simulation were close to the activity levels of the six lower-limb muscles measured in the electromyography experiment. In OpenSim simulation analyses of muscle activation levels and muscle forces, the muscle forces computed by computed muscle control are estimated by considering muscle activation

[20]

, while the inverse-dynamics calculation of muscle activation by static optimization not only considers the flexibility of the optimization problem

[21]

. The muscle forces and muscle activation levels estimated by the two methods are similar. The OpenSim static-optimization algorithm has been widely used for lower-limb muscles such as the vastus lateralis, biceps femoris, medial gastrocnemius, and tibialis anterior, and all have shown good agreement with electromyographic test data

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. It can therefore be inferred that the use of the OpenSim static-optimization algorithm to estimate activation levels of muscles such as the rectus femoris, lateral biceps femoris, vastus lateralis, vastus medialis, lateral gastrocnemius, and medial gastrocnemius is applicable to table-tennis technical movements. In addition, during the chasse-step, the activity levels obtained from electromyography were similar to the calculated muscle activations, indicating that the OpenSim model in this study is reliable.

Footwork technique affects the range of motion of table-tennis athletes. High-level table-tennis athletes can effectively use the lower limbs to transmit energy upward, thereby producing superior movement quality and technical performance

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. During the forward-swing phase of the chasse-step, male athletes had greater hip-joint contact forces in the anterior–posterior and medial–lateral directions than female athletes. This may be because rapid force output at the hip joint enables male athletes to move quickly to complete a rational and effective stroke, achieving high-quality athletic performance. Hip-joint motion is an important factor in energy generation and transfer in table-tennis movement. When table-tennis athletes strike the ball at an appropriate height, they usually produce greater hip-joint rotation

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. The hip-joint rotational moment plays an important role in producing horizontal swing speed in table-tennis athletes; the backward-directed moment of the hip joint and the upward-directed joint force of the hip jointly generate vertical velocity, thereby demonstrating higher stroke quality

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. During the chasse-step movement phase, larger hip-joint contact forces in the anterior–posterior and medial–lateral directions can help male table-tennis athletes increase stroke speed.

The ability of the knee joint to maintain stability under rapidly changing loads is an important factor affecting the dynamic stability of the knee joint. The greater superior–inferior knee-joint contact force in female athletes than in male athletes during the forward-swing phase may make female athletes more prone to load accumulation and overuse risk in the knee joint during the chasse-step. The knee joint plays an important role in the stroke action. During the swing, racket-sport athletes require superior–inferior extension of the knee joint to assist the racket' s trajectory from low to high

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. However, table-tennis athletes also show obvious weight-bearing at the knee joint during the forward-swing phase, and most professional table-tennis athletes have obvious symptoms of knee-joint pain

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; especially in women, during knee extension it may [[unclear: text continues beyond the visible page]].

lead to relatively substantial overuse injuries [30]. When executing footwork, table tennis players' knee joints are subjected to the greatest force in the vertical direction and to relatively large knee-extension moments. Such excessive mechanical loading can readily cause problems such as patellar tendinopathy and chondromalacia patellae [31]. Female athletes in particular should strengthen training of the muscle groups related to the knee joint in daily practice so as to prevent the occurrence of related injuries.

One limitation of this study is that it analyzed only the side-step footwork and did not extensively compare it with other footwork techniques. Because female athletes have a relatively high lower-limb body-fat percentage and greater variability in electromyographic signals, this study used only male surface electromyography data for model validation. Second, this study did not conduct an in-depth comparative analysis of the activation contributions of different lower-limb muscles. The lack of obvious activation of the tibialis anterior may be due to the fact that table tennis movements are characterized mainly by ankle plantarflexion, whereas activation of the tibialis anterior is mainly associated with ankle dorsiflexion. In addition, this study did not analyze biomechanical indicators of the upper limbs or the whole body [32–33], nor did it combine racket-striking analysis with refined musculoskeletal techniques for the upper limbs, wrists, and fingers. Future research may consider full-body modeling and simulation of table tennis technical movements.

4 Conclusion

By analyzing the joint contact forces in table tennis side-step footwork, it was found that during the stroke phase male athletes had greater hip-joint contact forces in the anteroposterior and mediolateral directions, whereas female athletes had greater knee-joint contact forces in the superior–inferior direction. Male athletes were better than female athletes at effectively using hip-joint force to increase the speed of swinging and striking the ball, but female athletes were more prone than male athletes to knee-joint load accumulation and potential overuse injury.

On the basis of sex differences in the biomechanical loads of table tennis athletes' footwork, it is recommended that coaches formulate and adopt individualized training programs for different sexes. Female athletes should pay attention to strengthening knee-joint stability and training of related muscle groups to prevent potential sports injuries. In addition, comparison of muscle activation verified that OpenSim modeling and simulation has relatively high reliability in analyzing table tennis technical movements and can be applied in future research on musculoskeletal modeling and simulation in table tennis biomechanics.

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Note: Figure translations are in progress. See original paper for figures.