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Article

Investigation research on the mechanism of knee joint injury in table tennis players landing before and after fatigue during stroke play

Penghui Zhang[1], Yuqi He[2], Shirui Shao[1,*], Wei Luo[3], Dongxu Wang[1], Julien S. Baker[1]

[1] Faculty of Sports Science, Ningbo University, Ningbo 315211, China
[2] Faculty of Engineering, University of Pannonia, 9700 Veszprém, Hungary
[3] Department of Physical Education and Military Training, Zhejiang Science Technology University, Hangzhou 330100, China
*** Corresponding author:** Shirui Shao, shaoshirui@nbu.edu.cn

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Abstract: This study investigated the relationship between lower extremity biomechanics and anterior cruciate ligament (ACL) injury in table tennis players before and after fatigue. We compared the biomechanical changes in the lower limbs of table tennis players during landing after completing a chasse-step while stroking, both before and after fatigue. A further aim was to examine ACL injury and provide a reference for training table tennis players. Ten national Level I table tennis players underwent lower extremity neuromuscular fatigue by running at a constant speed. Biomechanical data of the athletes were collected before and after fatigue. The effects of movement and characteristic time before and after fatigue on biomechanics were determined using a paired sample *t*-test. After fatigue, the angle of the ankle joint and the range of motion of the knee joint were significantly reduced ($p < 0.001$), while the angle of motion of the hip joint did not change considerably ($p = 0.747$). The angular velocity of the ankle and knee joints increased significantly after fatigue ($p < 0.001$), but the angular velocity of the hip joint decreased significantly ($p = 0.013$). Additionally, the ankle plantar flexion moment ($p = 0.003$), knee flexion moment ($p < 0.001$), and hip flexion moment ($p < 0.001$) increased significantly after fatigue. The ankle power ($p = 0.023$), knee power ($p = 0.009$), and hip power ($p < 0.001$) were significantly reduced throughout the landing cycle after fatigue. Fatigue in table tennis athletes reduces the sagittal plane buckling angle of the knee and ankle joints during landing. This change increases ground reaction and knee joint forces, significantly elevating the risk of knee injuries, including ACL tears. The reduced flexion angle exposes the knee to greater torque and diminishes its shock absorption capacity, heightening the risk of lower limb injuries. These findings underscore the need to address the impact of fatigue on landing mechanics in sports training and rehabilitation, emphasizing preventive measures.

Keywords: fatigue; table tennis; chasse step; anterior cruciate ligament (ACL) injury

1. Introduction

Table tennis is one of the most popular racquet sports in the world, with at least 40 million players participating as of 2016 [1]. In table tennis, the landing maneuver is the most basic movement technique in the stroking process, which can reflect the control ability of the lower limb neuromuscular system [2]. Therefore, athletes can land more safely by adjusting the landing position of their lower limbs, kinematic and dynamic characteristics, and neuromuscular feedback during exercise. However, it is still inevitable to be impacted by a magnitude of 3–7 times body weight in the initial stage of touching the ground [3], which increases the risk of injury in the landing action. Moreover, this risk will increase with the extension of exercise/load time, the gradual entry of the body into the fatigue state, and the decline of a landing control strategy [4].

Previous studies have found that different landing modes will cause different loads on the joints and ligaments of the lower extremities [5]. Injuries to the Anterior Cruciate Ligament (ACL) are particularly common during landing [6]. Granata et al. [7] found that women showed smaller joint stiffness than men at landing, which was an important cause of non-contact ACL rupture. At the same time, the valgus torque of the knee joint increased at or near exhaustion, indicating a decrease in the ability of the musculoskeletal system to maintain joint stability. After anterior cruciate ligament (ACL) injury, the patient's exercise level and quality of life are often seriously affected [8]. Since most ACL injuries are non-contact injuries [9], they can be prevented, and the prerequisite for injury prevention is to first determine the cause of injury. Some scholars believe that the forward shear force (that is, the sagittal load) borne by the proximal tibia is a more important risk factor for anterior cruciate ligament (ACL) injury than the pronation and pronation load of the knee joint [10], while other scholars believe that the internal and external pronation torque is the main factor for ACL injury [11]. Therefore, in this study, joint Angle change, joint torque, joint power, and angular velocity were selected to explore the relationship between the changes in lower limb biomechanics and ACL injury in table tennis players after fatigue during stroke play.

When the body is in a state of fatigue, the landing mode of movement may be affected, thus increasing the risk of ACL injury [12]. Compared to before fatigue, the maximum muscle contraction force after fatigue is significantly reduced [13], which means that the human body will land in a more unstable manner. Some studies have pointed out that fatigue can lead to smaller hip and knee flexion angles, larger knee valgus, and torque [14], some studies point out insufficient knee flexion and extension muscle strength, and imbalance of knee flexion and extension muscle strength during landing [15]. Therefore, exercise-induced fatigue may be one of the risk factors for ACL injury in table tennis players. However, in the current literature on the impact of fatigue factors on the biomechanics of lower limbs during landing, it is usually indicated that fatigue factors will increase the risk of anterior cruciate ligament (ACL) injury only through some indirect indicators [16]. How to effectively induce fatigue is the key to studying lower limb biomechanics during landing under fatigue. In general, when selecting the fatigue program, the laboratory mainly relies on the quantitative fatigue level, professional fatigue model, and scientific landing method [17].

This study aimed to investigate the mechanism of knee joint injury in table tennis players during landing while stroking before and after fatigue. By analyzing the kinematic changes of flushing-out and lower limbs of table tennis players in the process of landing with parallel steps before and after specific exercise fatigue, the kinematic characteristics caused by fatigue, especially the kinematic characteristics that may cause ACL injury, are understood. Accordingly, the fatigue scheme proposed by Quammen et al. [18] was adopted in this study to better understand the potential impact of fatigue on athletes' knee joints during competition. This study hypothesizes that the biomechanical characteristics of table tennis players' joints will change significantly during landing under exercise-specific fatigue. Specifically, compared to the pre-fatigue state, the knee flexion angle will decrease, while the knee valgus angle and valgus moment will increase post-fatigue. The decrease in lower limb muscle strength and control due to fatigue is expected to result in increased knee valgus, thereby elevating the risk of anterior cruciate ligament (ACL) injury.

2. Materials and methods

2.1. Participants

Ten national first-class table tennis players were selected as the experimental subjects. The specific information of these 10 subjects is shown in **Table 1**. The average age of these 10 subjects is 20 ± 1.30 years old, the average height is 1.73 ± 3.36 cm, the average weight is 64 ± 7.83 kg, and the average training period is 11 ± 2.3 years. All enrolled subjects were right-handed, with a right leg as their inertial leg, and were required to have no foot deformities in the past six months, no severe musculoskeletal injuries to the lower extremity, no history of lower extremity surgery, and no other injury factors that might interfere with the study. All subjects were informed of the purpose, requirements, and procedures before the start of the experiment. The experimental scheme was approved by the Ethics Committee of Ningbo University (approval number: RAGH20240513), and all subjects signed written informed consent.

Table 1. The participants' characteristics and information.

Population	Age（year）	Height（cm）	Weight（kg）	Training Time (year)
10	20 ± 1.30	174 ± 3.36	64 ± 7.83	12 ± 2.3

Figure 1. The anatomical locations of markers attached to the table tennis athlete.

2.2. Finite experimental protocol and equipment

The experimental tests used in this study were carried out in the Laboratory of Sports Biomechanics of Ningbo University. The height and weight of all participants were measured and recorded before the formal experiment commenced. During the test, the 3D kinematics data of the hip, knee, and ankle joints of the lower extremity were collected by the Vicon 3D infrared motion capture system (Vicon Metrics Ltd., Oxford, United Kingdom), and the acquisition frequency was set at 200 Hz. Reflective markers with a diameter of 14 mm were placed in the corresponding position on the body surface of runners' lower limbs, and the Vicon infrared motion capture system was used to capture motion tracks. At the same time, the AMTI three-dimensional force measuring platform (AMTI, Watertown, Massachusetts, USA) was placed in the center of a designated runway to synchronously collect the ground reaction force parameters, and the collection frequency was set at 1000 Hz. The Gait2392 model was selected to simulate participants' movements in OpenSim (Stanford University, Stanford, CA, United States) and to replicate the placement of 39 reflective markers (14 mm in diameter) based on a previous study by Delp et al. [19]. However, since the experiment did not analyze head movement, the overhead markers in the model were dropped during the experiment, leaving 38 reflection markers. During the experiment, participants used a unified racket (Butterfly Tenergy 05 Max and DHC Hurricane 3 rubber sheets), a ball (D40+, Double Happiness Sports Company, Shanghai, China), a ball table (Rainbow, Double Happiness Sports Company, Shanghai, China), and table tennis shoes and tights. The heart rate meter manufactured by Suunto of Japan is used for real-time monitoring of the subjects' heart rate during fatigue induction to ensure the effectiveness and experimental safety of fatigue induction.

2.3. Procedure

Before data collection began, each subject performed 8 min of static stretching, followed by 5 min of jogging at a speed of 2.0 m/s on the running platform, and then all participants were asked to wear a uniform style of tights, leggings, and sneakers. The experimental operator affixed the reflector to collect the static model of the subject before fatigue. The positions of the reflective ball are 39 points, including left and right acromion, head, chest, left anterior iliac, right anterior iliac, internal knee, external knee, thigh tracking point, calf tracking point, internal ankle, external ankle, 1st metatarsophalangeal joint, 5th metatarsophalangeal joint, and heel (**Figure 1**). After that, the subjects were familiar with the experimental environment and then conducted a 5-min batting training to ensure that the subjects were in a normal state during the formal experiment.

When the command begins, the server serves from the opposite side of the ball table in a fixed position, and the subject performs the chasse-step method to receive the ball. Each time he hits the ball, his right leg must step on the force measuring table, and the ball must be hit on the opposite side of the ball table each time to be effective (see **Figure 2**). In addition, a 15-second rest was required for each successful shot to ensure that the subjects could play the ball without fatigue. The entire test was conducted in two rounds: the first round of batting in a non-fatigued state, followed by the second round of batting immediately after fatigue induction. Each round of testing required 5 successful data collections. Participants were required to monitor fatigue-induced heart rate in real-time monitoring (maximum heart rate, average heart rate), and additionally used the subjective fatigue rating scale (RPE) as an auxiliary fatigue degree of determination. Subjective fatigue was assessed according to the Session Rating of Perceived Fatigue (RPE) scale, which is rated on a scale of 6 to 20, with level 6 defined as easy (heart rate < 70) and level 19–20 as extremely hard (heart rate ≥ 195) [20].

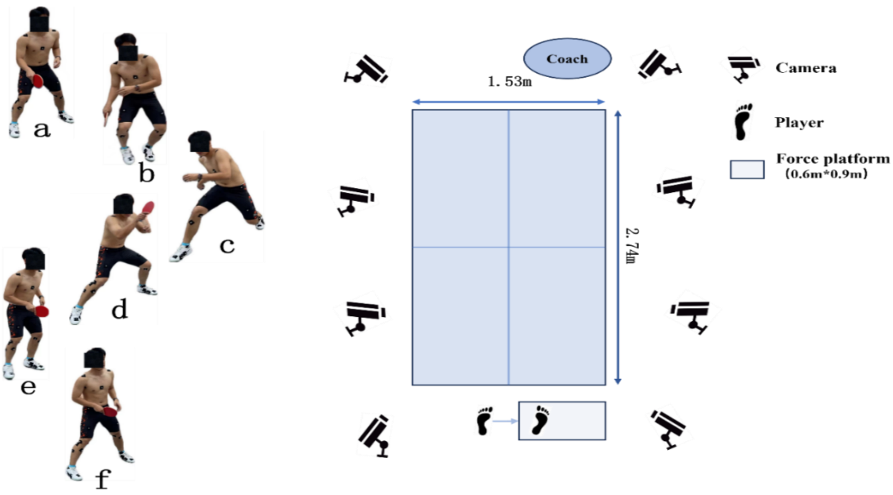

Figure 2. The left side of the picture shows the technical performance of the subjects during the test. **(a–c)** The initial phase of the landing process; **(c–e)** the landing phase of the landing process; **(e–f)** the push-off phase of landing.

2.4. Fatigue scheme

Lower limb fatigue is one of the most likely to cause fatigue in table tennis, and running is one of the most likely to cause lower limb fatigue. Based on past research, the methods to produce fatigue include constant speed running and variable speed running plus jumping. In this study, constant speed running is selected as the way to produce fatigue. Constant speed running fatigue program (“Running fatigue Program “). According to the fatigue scheme proposed by Quammen et al. [18], subjects were required to run at a constant speed of 4 m/s on the running platform until they could not maintain the predetermined intensity to continue running. After stopping the exercise, the treadmill speed was reduced to 1 m/s, and the subjects were required to continue walking for 2 min before the landing experiment. The exercise can be terminated when the following two conditions are met: 1) The subject’s heart rate reaches 85% of the maximum heart rate of the current age, and 220 minus age is defined as the maximum heart rate in this study; 2) The subject's subjective fatigue degree can be judged according to the Session rating of perceived exertion (RPE scale), which is divided into grades ranging from 6 to 20. This study defines fatigue as RPE above 17; 3) The subject cannot continue to exercise.

Table 2. Physical state of athletes during the experiment.

	Completion Time（s）	Heart Rate（once/min）	RPE
Pre-fatigue test	237 ± 98.5	81.6 ± 8.5	7.5 ± 0.5
Fatigue intervention	346 ± 32.1	167.4 ± 9.6	17.0 ± 1.5
Post-fatigue test	198 ± 64.5	170.1 ± 10.2	17.5 ± 1.5

When the subject was identified as having reached a fatigued state, the fatigue test was performed immediately. The test action is consistent with the requirements before fatigue, but there is no rest time between each test in the post-fatigue test, which is also to maintain the fatigue effect. Throughout the test, the time to complete the movements and the immediate heart rate of the subjects were recorded, and the results are shown in **Table 2**.

2.5. Data processing

According to previous studies, the landing period in this study was defined as the initial contact with the ground to the maximum knee flexion, where the initial contact with the ground was the vertical ground reaction force measured by the force measuring table greater than 10 N [21]. When the ground reaction force decreases to 10 N for the first time, it is defined as the push-off stage [22]. The Vicon Nexus 1.8.6 software was used to identify and acquire the GRF and kinematics data of the parallel step method, and the data of 2 to 3 seconds before landing was intercepted. Then the collected reflective marking points were named, and the missing marking points were patched at the same time. Then the intercepted data was exported in .c3d format. MATLAB R2023a (The MathWorks, Natick, MA, USA) was used for coordinate transformation, data extraction, and format conversion of all data. Then, the static model collected was scaled in OpenSim, and the .trc data and. mot data converted from MATLAB were calculated in OpenSim for their inverse kinematics and inverse dynamics.

2.6. Statistical analysis

All the data were extracted from the dominant leg (right leg) to obtain the skewness and peak value of each kinematic index, and all the obtained parameters were represented by the mean ± standard deviation. In this study, a paired sample *t*-test was used to compare the biomechanical differences between the subjects before and after fatigue. All statistical analyses were performed using SPSS 27.0 software, and the significance level p was set to 0.05.

Table 3. Comparison of the significance of angle, moment, angular velocity, and power of each joint before and after fatigue.

	Parameters	**Pre**	**Post**	***P*-value**
Hip	Angle	59.29 ± 17.53	59.10 ± 12.33	0.747
	Moment	19.24 ± 7.52	21.45 ± 8.51	0*
	Velocity	−53.72 ± 127.06	−39.66 ± 11.32	0.013*
	Power	−327.79 ± 2910.32	154.97 ± 2659.37	0*
Knee	Angle	−59.19 ± 15.09	−65.10 ± 11.86	0.016*
	Moment	−4.17 ± 4.41	−1.89 ± 2.33	0*
	Velocity	−1.78 ± 178.27	−22.78 ± 140.48	0.002*
	Power	246.63 ± 1024.89	29.66 ± 242.73	0.009*
Ankle	Angle	−2.69 ± 6.01	−0.37 ± 4.80	0*
	Moment	0.86 ± 0.18	0.90 ± 0.15	0.003*
	Velocity	−38.76 ± 107.79	−18.37 ± 86.14	0*
	Power	−28.54 ± 99.58	−21.65 ± 85.53	0.023*

Notes. Pre, before fatigue; Post, after fatigue; *Refers to significance with $p < 0.05$.

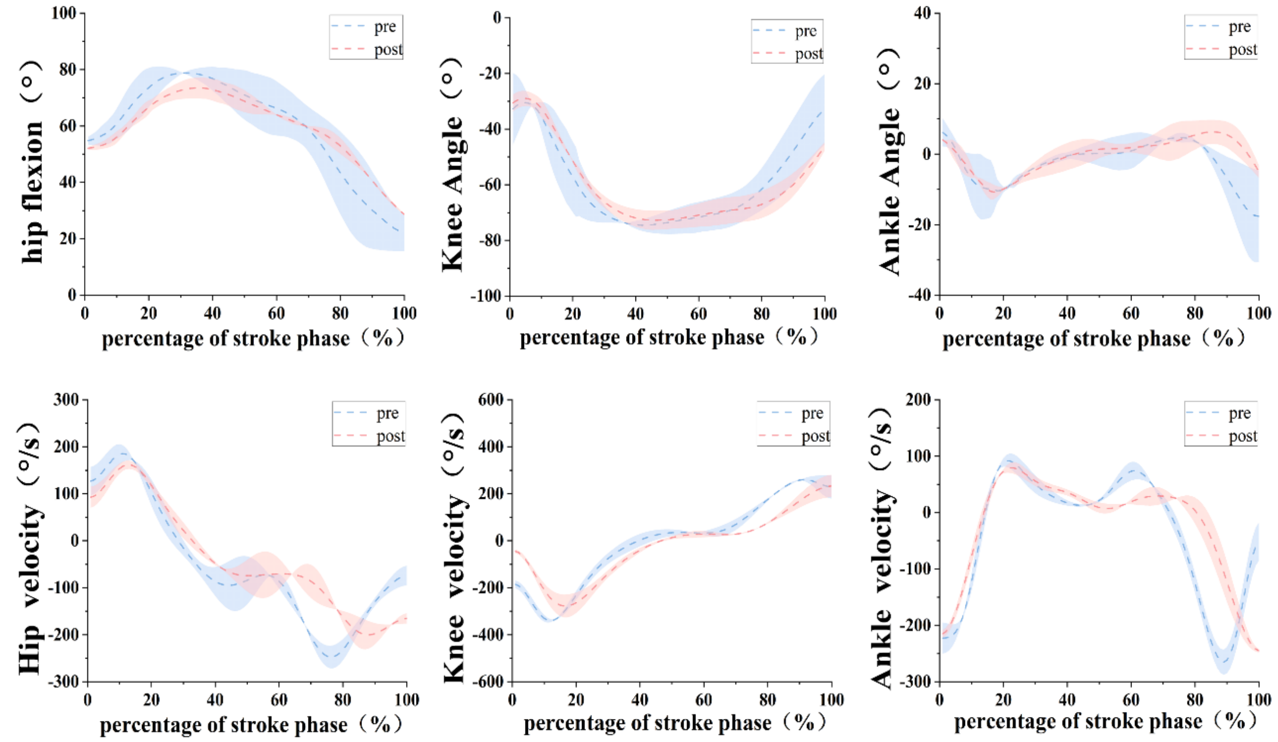

Figure 3. Changes of Angle and angular velocity above the sagittal plane of the hip, knee, and ankle before and after fatigue. Pre, before fatigue; post. after fatigue, the dashed line represents the mean, and the color interval portion represents the standard deviation.

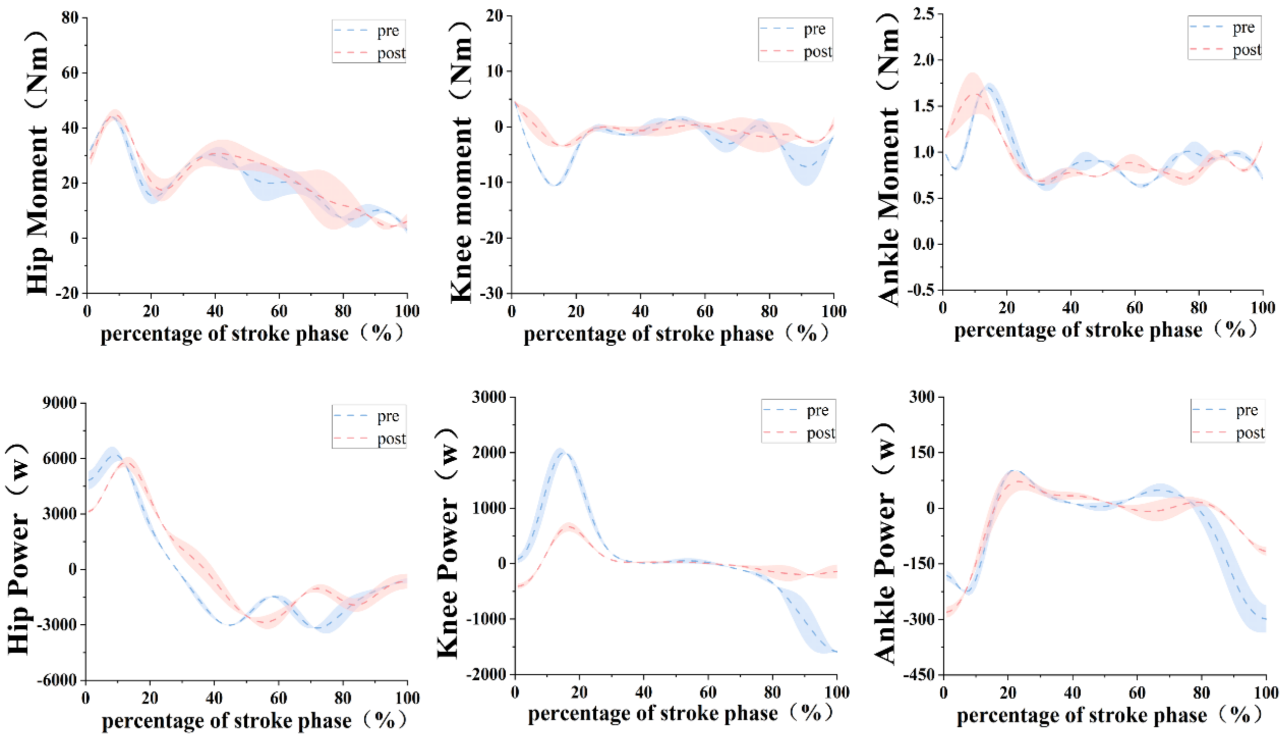

Figure 4. Changes of torque and power above the sagittal plane of the hip, knee, and ankle before and after fatigue. Pre, before fatigue; post, after fatigue; The dashed line represents the mean, and the color interval portion represents the standard deviation.

3. Result

3.1. Angular change

As shown in **Figure 3** and **Table 3**, in the sagittal plane, the ankle Angle of landing after fatigue was significantly (p < 0.001) lower than that of landing before fatigue during the whole landing cycle. The angular range of motion of the knee joint after fatigue landing was less than that before fatigue landing during the whole landing cycle (p = 0.016). The motion Angle of the hip joint after fatigue did not change significantly compared with that before fatigue (p = 0.747).

3.2. Joint angular velocity

As shown in **Figure 3** and **Table 3**, in the sagittal plane, the angular velocity of the ankle after fatigue landing is significantly greater than that before fatigue landing during the landing period (p < 0.001), the angular velocity of the knee after fatigue landing (p < 0.001) is significantly greater than that before fatigue landing, and the angular velocity of the hip after fatigue landing (p = 0.013) is significantly smaller than that before fatigue landing.

3.3. Joint moment

In the sagittal plane, as shown in **Figure 4**. The true plantarflexion moment (p = 0.003) of the ankle joint after landing was significantly greater than that before landing. The knee flexion moment after fatigue landing (p < 0.001) was significantly higher than that before fatigue landing. The buckling moment (p < 0.001) after hip joint fatigue landing was significantly higher than that before hip joint fatigue landing.

3.4. Joint power

As shown in **Figure 4**, the ankle joint power after fatigue landing is significantly lower than that before fatigue landing during the entire landing cycle (p = 0.023), and the knee joint power after fatigue landing is significantly lower than that before fatigue landing during the entire landing process (p = 0.009). The power of hip joint landing after fatigue was significantly lower during the whole landing (p < 0.001) than that before fatigue.

4. Discussion

This study examined how table tennis players hit the ball before and after fatigue when landing and compared several lower limb biomechanical comparisons. According to SPSS analysis of the results of sagittal joint Angle (as shown in **Table 3**), the table tennis athletes' fatigue after stroke playing the ball, resulted in the entire cycle during knee flexion significantly reducing (p = 0.016), This is a manifestation of a "hard" landing. A hard landing is thought to increase the risk of lower extremity injuries, especially increasing the risk of non-contact ACL injury [23]. The angle of flexion usually leads to greater joint torque, thus significantly increasing the risk of lower limb joint damage [24]. The results of the present study are consistent with this view, as measured by the joint torques of the hip and knee in the sagittal plane, the torques of the knee and hip during post-fatigue landing were significantly higher than those during pre-fatigue landing throughout the cycle. In the process of landing, the lower limb load is distributed from the foot and ankle at the bottom of the distal to the load transfer mode, then the load gradually spreads to the knee and hip joints, and the knee joint plays a major role in cushioning [25]. The sagittal view of the present study results is consistent with most previous studies. Studies have found that subjects with fatigue consciously change the landing technology of the lower limb, such as reducing knee buckling [26]. Players experience Orishimo fatigue after landing and hip flexion angle decreases, but there are no statistical differences in knee [14]. MCLEAN [27] and others found that the fatigue after landing at the knee flexion Angle decreased, and at the hip, there was no significant difference. The reason is that after fatigue athletes when trying to maintain stability in the process of landing, consciously increase landing flexion of the knee and hip joint angle, leading to a hard landing and increasing the ground reaction force. Especially the knee joint, as an important connection between the ankle and hip joints, damping effect in the process of impact load transmission [28], this will inevitably cause the landing after fatigue to produce a larger joint reaction force, which increases the risk of ACL injury [29].

There is also research that presents the results of the study, on the other hand, namely in the process of fatigue after landing angle of the knee and hip flexion compared to the former increased fatigue. Such as Coventry's research result suggests that in the process of fatigue after landing the knee and hip flexion angle increases and this is due to the fatigue work redistribution after the compensation reaction [30]. Researchers found that in male and female subjects such as Brazen, landing after fatigue knee flexion angle is bigger, and think that fatigue after landing increases the risk of landing leg injury also needs further exploration, but changes in the results are because of the single leg landing [31]. Kernozek and others found that male subjects than female subjects showed greater knee flexion Angles, and concluded that neuromuscular fatigue can cause women of lower limb biomechanics changes, the result increasing non after an ACL injury risk [32].

The reason why different studies can get different results in knee and hip flexion Angle changes during post-fatigue landing is mainly due to the different fatigue intervention methods selected by each of them. Some research for a specific muscle fatigue intervention, while others use the open chain intervention methods, such as running or like this in the study of constant speed run fatigue intervention plan. In addition, the differences in the control variables in the experiment lead to different degrees of fatigue in the subjects, some of which are only manifested as certain muscle fatigue, and some are generalized voluntary sensory fatigue or nervous fatigue of the whole lower limb, resulting in different experimental results. Landing test conditions, such as single-leg landing, the landing legs, jumping, falling vertical take-off, and landing, also must be considered mainly in follow-up studies. Gender- and subject-level differences should also be examined. Part of the study only selects male or female subjects, or healthy individuals, while other studies include high-level athletes, such as basketball, football, and handball players, further affecting the differences in the results of the study. However, this study and previous related studies have shown that the use of the parallel step method during batting in table tennis players after fatigue will lead to reduced knee flexion in the sagittal plane, thereby increasing the ground reaction force and knee reaction force, increasing the risk of knee injury including ACL injury.

This study also has certain limitations, first of all, Our experiment was based on laboratory environment collection, and there was a gap with the real competition, the subjects of this study group were limited to male table tennis players, and on the surface of previous research, women than men in landing showed smaller joint stiffness, which is the important cause leading to the non-contact ACL rupture [7]. Secondly, since the chasse-step method is the most common in table tennis, but the one-step method and the cross-step method are also often used in mixed movement, this study only uses the chasse-step method to explore the mechanism of knee joint injury in the landing process before and after fatigue, and whether other steps are also different needs further discussion and explanation.

5. Conclusion

This study investigated the mechanism of knee joint injury in table tennis players under fatigue before and after a stroke playing the ball. The findings indicate that fatigue can lead athletes to adopt a “hard landing” approach, increasing the risk of non-contact anterior cruciate ligament (ACL) injuries. When fatigued, athletes are more prone to using a “hard landing,” which results in greater impact forces on the knee joint, consequently elevating the risk of knee injury. To mitigate this risk, players can enhance the energy dissipation of the knee and hip joints by increasing the flexion amplitude of these joints during strokes. An increased range of flexion helps reduce the impact forces on the knee and hip joints, thus lowering the likelihood of lower limb joint injuries. To reduce the risk of knee injuries under fatigue conditions, athletes should focus on controlling knee and hip flexion during training and competition. Additionally, targeted flexibility and stability training should be emphasized to improve joint flexibility and stability. By implementing these measures, table tennis players can effectively reduce the risk of knee and hip joint injuries, thereby maintaining their performance and prolonging their athletic careers.

Author contributions: Conceptualization, PZ and SS; methodology, YH; validation, WL, DW and SS; formal analysis, PZ; investigation, PZ; resources, JSB; writing—original draft preparation, PZ; writing—review and editing, SS; supervision, JSB; funding acquisition, SS. All authors have read and agreed to the published version of the manuscript.

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board Ningbo University (RAGH20240513, Approval Date: 13 May 2024).

Informed consent: Informed consent was obtained from all subjects involved in the study.

Data availability statement: The authors will make the raw data supporting the conclusions of this article available without undue reservation.

Conflict of interest: The authors declare no conflict of interest.

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