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Article

Sex differences in kinematics and muscle activity during the impact phase of a single-leg landing task after a backhand side overhead stroke in badminton

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Abstract: Background: Female badminton players have a higher risk of anterior cruciate ligament (ACL) injury in landing maneuvers compared to males. Gender differences in neuromuscular control may be a potential risk factor for the increased incidence of ACL injury in female badminton players. **Study design:** Controlled laboratory study. **Methods:** Sixteen badminton players (8 male, 8 female) participated in a badminton single-leg landing task in which lower limb kinematics, ground reaction forces, and lower limb muscle activity were measured using a marker-based motion capture system, force plates, and electromyography (EMG). An analysis of variance (ANOVA) was used to analyze gender differences in leg kinematic data, mean normalized leg muscle activation (MVC%), and muscle co-contraction during the impact phase after landing. **Results:** During the impact phase of the badminton landing task (100 ms after initial contact), the knee valgus angle at the moment of initial contact (IC) and posterior peak ground reaction force (GRF) was greater in females than in males (6.27 ± 2.54 vs 1.84 ± 3.28) and (6.16 ± 2.83 vs 0.88 ± 2.59). Knee flexion angle and ankle plantarflexion angle were less in females than in males at the moment of peak posterior GRF (16.71 ± 4.20 vs 23.90 ± 5.04) and (−28.34 ± 5.60 vs −37.05 ± 7.17). During the post-landing impact phase, compared to male badminton players, females exhibited greater rectus femoris (51.85 ± 15.68 vs 19.73 ± 6.63) medial hamstring (44.88 ± 19.07 vs 20.54 ± 10.16), medial gastrocnemius (66.23 ± 21.42 vs 38.21 ± 15.16) lateral gastrocnemius (79.43 ± 22.54 vs 46.53 ± 13.17) muscle activity. In addition, males exhibited a higher co-contraction ratio of the medial and lateral gastrocnemius compared to female athletes (1.44 ± 0.46 vs 0.99 ± 0.24). **Conclusion:** There were significant gender differences in neuromuscular control (muscle activity patterns, movement patterns) between badminton players during the impact phase of the badminton single-leg landing task. These findings highlight the need for gender-specific training programs to address neuromuscular differences and reduce ACL injury risk in badminton players.

Keywords: badminton; single-leg landing; ACL injury; kinematics; EMG

1. Introduction

Badminton is gaining popularity as an over-the-net confrontational racquet-swinging sport and is attracting many female athletes to participate in it [1]. Despite this popularity, there is less research on badminton-related injuries. Due to the nature of badminton, there are fewer contact injuries and badminton injuries occur mainly in non-contact movements such as jumping, landing, and changing directions [2]. Lower extremity injuries are the most common injuries in badminton. ACL injuries are considered one of the most serious lower extremity injuries, accounting for approximately 26% of all knee injuries [2]. Previous studies have shown that female athletes have a higher incidence of ACL injuries, about 2–6 times higher than males [3,4]. Like other sports, high ACL injury rates also plague female badminton players [2,5]. In a Japanese study on ACL injuries in junior and senior high school athletes over a decade, it was noted that the incidence of ACL was higher in females than in males (1.36:0.48), with the incidence of ACL injuries in female junior and senior high school badminton players being 4.2 and 4.8 times higher than in males, respectively [5]. Therefore, it is crucial to understand why female badminton players have a high risk of ACL injuries to prevent such injuries.

Due to the higher incidence of ACL injuries in female athletes, researchers have extensively explored the gender differences in factors that may contribute to ACL injuries, with most proposing a variety of factors, including hormonal and menstrual cycles, as well as anatomical, genetic, and neuromuscular control differences between male and female athletes [6,7]. Because the preceding items are more difficult to modify whereas neuromuscular control factors can be altered through their active activities, they have recently received increasing and widespread attention [7]. Understanding the kinematic and neuromuscular differences in specific movements may help explain the gender differences in ACL risk rates. Previous studies have shown a preference for a quadriceps-dominated landing pattern in women compared to men during landing tasks [8,9], and when women contract their quadriceps, they pull the knee joint to produce extension, which may be related to the fact that females have always been observed to use a more extended landing position [10]. The quadriceps is often considered the antagonist muscle of the ACL. The quadriceps are attached to the proximal tibia via the patellar ligament, and at low flexion angles, quadriceps contraction increases the anterior displacement of the tibia relative to the femur causing increased stress and strain on the ACL. Ebben et al. [11] found in a study of side-cutting tasks that males exhibited greater medial and lateral hamstring activation than females. In contrast to the greater medial hamstring activation in females in the landing task study by de Britto et al. [12]. This may be because it is at greater than 30 degrees that co-activation of the hamstrings can affect ACL protection, with the hamstrings acting as a synergist for the ACL at this time, and contraction to generate backward shear can help counteract the anterior shear forces that put the ACL at increased risk of injury, whereas, at smaller knee flexion angles (less than 22 degrees), hamstring activity may be detrimental to the protection of the ACL [13]. Numerous studies have shown that the gastrocnemius muscle is the primary provider of anterior tibial shear forces and is associated with increased ACL loading. Beaulieu et al. [14] and Landry et al. [15] in a study of male and female elite soccer players performing unintended cutting landings showed that females exhibited greater gastrocnemius muscle activity compared to males. In addition, muscle co-activation is closely related to knee stability and poor co-activation patterns that cause the knee in abnormal postures may be associated with high ACL injuries in females [8,16]. Although previous studies have evaluated sex differences in neuromuscular control, however, there are contradictions between the results of these previous studies on sex differences in neuromuscular control due to factors such as different sports, different training received by the participants, and different types of tasks [16]. Therefore, for badminton players, sex differences in neuromuscular control for specific badminton functional tasks that lead to ACL injury need further exploration.

As different forms of landing in different sports (side cutting landing in football, drop landing in skiing, jump landing after a block or kill in volleyball) lead to different risk factors for ACL injuries [17–19], ACL injuries in badminton players mainly occur in the single-leg landing manoeuvre after a backhand side overhead stroke. Our previous study showed that there are gender differences in muscle pre-activation and kinematics in badminton players during the pre-landing preparation phase [20], however knee stability requires a combination of pre-landing muscle pre-activation and post-landing reflexive muscle activation to prevent injury [21]. In order to investigate the reasons for the higher risk of injury in females compared to male badminton players in a single-leg landing task, we investigated gender differences in neuromuscular control patterns during the post-impact phase of landing. The aim of our study was to initially investigate gender differences in muscle activity during the impact phase of a high-risk single-leg landing task in badminton players and to combine this with kinematic data analyses to better help badminton coaches, athletes, and rehabilitators to understand potential risk mechanisms that may contribute to the high prevalence of non-contact ACL injuries in females. We hypothesised that 1, badminton players would exhibit greater rectus femoris, medial hamstring and gastrocnemius muscle activity during the early impact phase of the single-leg landing task compared to males; 2, there would be gender differences in the co-activation of lower limb muscles during the landing impact phase of the single-leg landing task; and 3, there would be gender differences in the movement patterns of badminton players during the single-leg landing.

2. Methods

2.1. Participants

16 badminton players participated in this study, including 8 males and 8 females. The females were 21.50 (±2.45) years old, 1.67 (±0.05) m tall, and 59.50 (±5.71) kg in weight, while the males were 20.63 (±0.92) years old, 1.78 (±0.03) m tall and 71.63 (±9.97) kg in mass, Years of training were 11.88(±3.18) for females and10.38(±1.69 for males), none of the subjects included had a history of injury. The following inclusion criteria were met by all participants recruited by Jeonbuk University: (1) no significant motor limitations or muscle weakness resulting from observation and brief assessment by an experienced physiotherapist; (2) no lower limb pain before testing; and (3) at least four times a week, participants had to participate in organized training. For standardized testing, badminton players with the right hand as the dominant hand were selected as the study participants. Before participating in the study, all Participants were informed of the trial procedures and read and signed an informed consent form.

2.2. Prepare for testing

We used 13 infrared cameras (OptiTrack, LEYARD, Buffalo Grove, IL, USA) to collect trial data to capture kinematic data from each participant. These cameras had a sampling rate of 120 Hz. Whole-body kinematic data were tracked using 57 marker points throughout the body, with the reflex markers located at anatomical locations as shown in **Figure 1** [22].

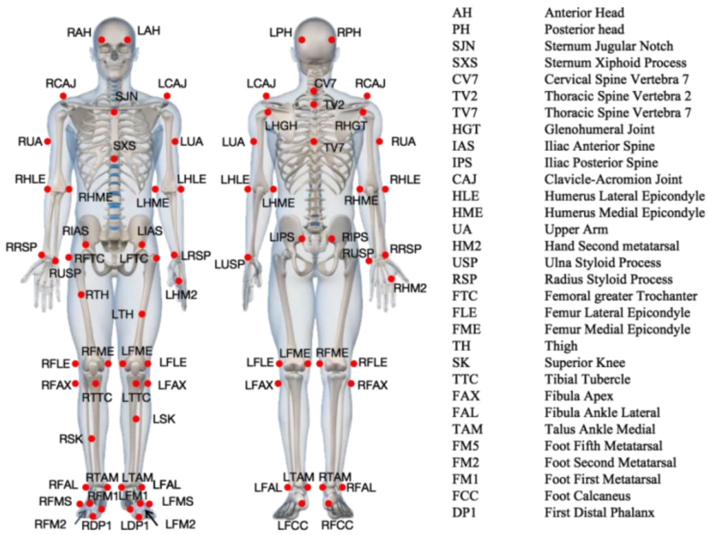

Figure 1. Anatomical position of the reflex marker ($N = 57$). "L" and "R" represent the left and right sides.

The ground reaction force data were collected at 1200 Hz using an OR6-6-2000 force platform (AMTI Inc., Newton, Maryland, USA). The maximum delay time was 6 ms.

The EMG collection system (Trigno Avanti Sensor, Delsys, USA) was selected as the EMG data acquisition device. For the EMG signal acquisition, we used a Trigno Avanti sensor (Delsys, Natick, MA, USA; 3.7 cm × 2.7 cm). All EMG sensors (Trigno Avanti Sensor) had a common-mode rejection ratio of 80 dB and were synchronized with kinematic and kinetic data by recording software (OptiTrack, LEYARD, USA) and EMG was sampled at 1200 Hz.

The electrodes were positioned on the surface of gluteus maximus (GMAX), gluteus medius (GMED), rectus femoris (RF), medial semitendinosus (MH), lateral biceps femoris (LH), medial gastrocnemius (MG), and lateral gastrocnemius (LG) muscles, and the methodology for the maximal voluntary isometric (MVIC) test is referenced from our previous study [20].

Use Fengcai's badminton server SPT6000 (SPTLOOKER, China) to send the shuttlecock to the designated area in the same state. Participants wear uniform shorts, individual socks, and shoes, and use uniform rackets.

2.3. Test procedure

The design of the laboratory, concerning our previous research [23], is shown in **Figure 2**.

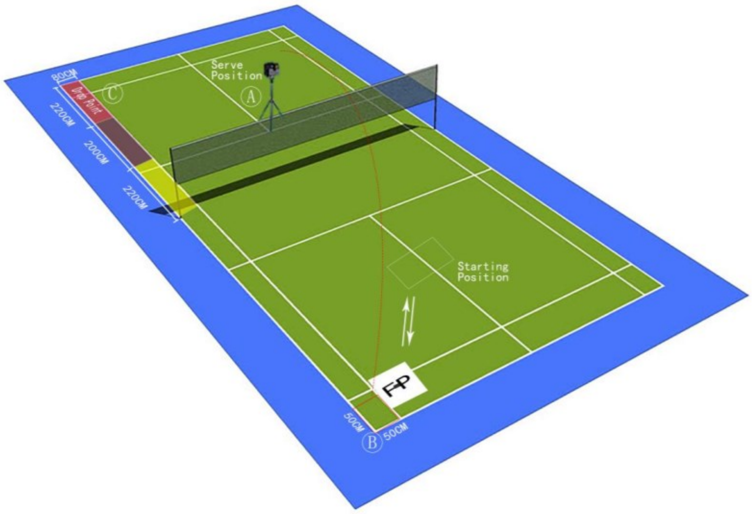

Figure 2. Laboratory setup, the position of the force plate (FP), and the badminton serve machine.

Note: The badminton serving machine sends the shuttlecock from area A to area B, with a size of 50 cm × 50 cm. The red arrows indicate the trajectory of the shuttlecock. The participant steps backward from the starting point in a leftward direction, then jumps off their right foot, performs an overhead strike, lands on the force plate with their left foot, and quickly returns to the starting position. Area C is the landing point of the shuttlecock after it is struck. (This figure was generated by the author through Adobe Photoshop software).

The participants engaged in a 10-min warm-up exercise (including jogging and swinging), followed by a single-leg landing test after performing a backhand side overhead stroke, which is considered to have the highest incidence of ACL injuries. A badminton coach with approximately 10 years of competitive playing experience demonstrated the footwork and overhead stroke task to each participant. Starting from the initial position, the participants simulated a backhand side step towards the left rear of the court, performed an overhead stroke, landed on the force plate with their left leg, and quickly returned to the starting position. The participants hit the shuttlecock to the back side of the opposite court in their usual manner. Participants were allowed to perform several exercises, followed by three to five consecutive trials.

3. Data processing and analysis

The kinematic data were processed by Visual 3D (C-Motion, Inc., Germantown, MD, USA). The pelvis was defined relative to the global (laboratory) coordinate system and assigned six (three translational and three rotational) degrees of freedom. The pelvis, thighs, and calves were defined with the positive y-axis pointing anterior, the positive x-axis pointing medial, and the positive z-axis pointing superior. The hip joint angle is defined as the angle between the thigh and the pelvis, the knee joint angle is defined as the angle between the lower leg and the thigh, and the ankle joint angle is defined as the angle between the foot and the lower leg. The motion of the hip and knee joints is defined as flexion/extension around the X-axis (medial-lateral axis) in the sagittal plane, adduction/abduction around the Y-axis (anterior-posterior axis) in the coronal plane, and internal/external rotation around the Z-axis (vertical axis) in the horizontal plane. The motion of the ankle joint is defined as dorsiflexion/plantarflexion around the X-axis (medial-lateral axis) in the sagittal plane, inversion/eversion around the Y-axis (anterior-posterior axis) in the coronal plane, and abduction/adduction around the Z-axis (vertical axis) in the horizontal plane, with the direction determined by the right-hand screw rule. By assigning positive and negative signs, the directions of hip and knee joints are unified as positive for flexion, negative for extension, positive for adduction, negative for abduction, positive for internal rotation, and negative for external rotation. It should be noted that in ankle joint angles, the angle of 90 degrees between the foot and the sagittal plane of the lower leg is defined as 0 degrees in anatomical standing, dorsiflexion (positive) represents upward movement, plantarflexion (negative) represents downward movement, inversion (positive) represents inward movement, eversion (negative) represents outward movement, abduction is positive, and adduction is negative.

The first frame when the force plate data began to increase was defined as the moment of initial contact and we analyzed muscle activity within 100 milliseconds(ms) of initial contact, in addition, we processed and analyzed kinematic data from the moment of initial contact and the moment of peak posterior ground reaction force as these data were considered important for the analysis of ACL injury.

The EMG activity data were analyzed by the software accompanying the EMG collection system (Trigno Avanti Sensor, Delsys, USA) with a band-pass filter of 10-400Hz, using a The EMG signals were corrected and smoothed using root mean square (RMS) with a 20 ms window. The mean RMS amplitude was calculated for each muscle over three trials and then normalized according to the normalized RMS of the MVIC. The duration of co-contraction was calculated as the activity time of a pre-defined muscle pair (from the last muscle in the pair to start activation and the first muscle in the pair to stop activation) [24] and expressed as a percentage of IC to 100 ms after the IC phase. Calculation of the ratio of muscle activity (IEMG) between the two groups of muscle co-contraction periods during the post-landing impact phase [25,26]. Four co-contraction indices were calculated: 1) co-contraction of hamstrings and quadriceps (H/Q); 2) co-contraction of gastrocnemius/quadriceps (GAS/Q); 3) co-contraction of medial and lateral hamstrings(M/LHAM); and 4) co-contraction of medial gastrocnemius and lateral gastrocnemius(M/LGAS).

A one-way ANOVA was used to test for statistical differences between male and female badminton player groups. The outcome variables were as follows: normalized electromyographic activity (MVC%) of the lower limb muscles; co-contraction index of the lower limb muscles; and hip-knee-ankle joint angle. Statistical analyses were performed using SPSS 26.0 software (SPSS for Windows, Chicago, IL, USA) with a significance level of $p < 0.05$.

4. Results

The mean and standard deviation of lower limb muscle activity during the post-landing impact phase of a single leg landing task after a backhand side overhead stroke in badminton, as shown in **Figure 3**.

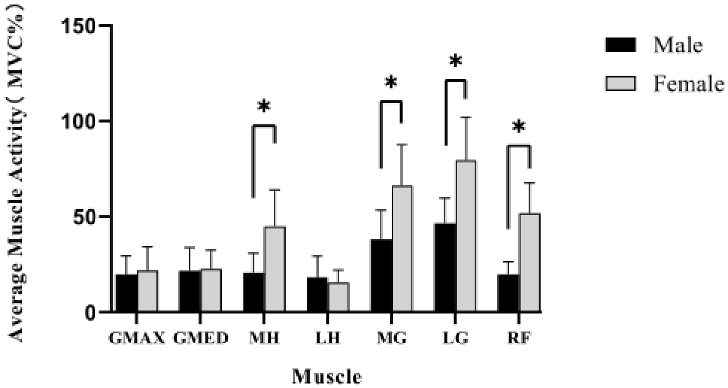

Figure 3. Badminton single-leg landing task, mean and standard deviation of lower limb muscle activity during the post-landing impact phase.
* Represents statistically significant differences.

In the badminton single-leg landing task, the standardized medial hamstring muscle activity values were 44.88 ± 19.07 in female badminton players and 20.54 ± 10.16 in males early in the post-landing impact phase. The medial hamstring activity was 24.34% higher in female badminton players than in males, with a highly significant difference between female and male badminton players ($p < 0.05$). The standardized medial gastrocnemius muscle activity value was 66.23 ± 21.42 in female badminton players and 38.21 ± 15.16 in males. The activity of the medial gastrocnemius muscle was 28.02% higher in female badminton players than in males and there was a significant difference between female and male badminton players ($p < 0.05$). The standardized muscle activity value of lateral gastrocnemius was 79.43 ± 22.54 in female badminton players and 46.53 ± 13.17 in males. The activity of lateral gastrocnemius was 32.90% higher in female badminton players than in males and there was a highly significant difference between female and male badminton players ($p < 0.01$). The standardized rectus femoris muscle activity values were 51.85 ± 15.68 in female badminton players and 19.73 ± 6.63 in males. The rectus femoris muscle activity was 32.12% higher in female badminton players than in males and there was a highly significant difference between female and male badminton players ($p < 0.05$).

The gender differences in lower limb muscle co-activation during the post-landing impact phase in the single-leg landing task in badminton are shown in **Figure 4**. In the single-leg landing task, during the post-landing impact phase, the co-activation ratio of the medial and lateral gastrocnemius muscles was 0.99 ± 0.24 in female badminton players and 1.44 ± 0.46 in male badminton players, which was 0.45 higher in males than in females, and there was a significant gender difference ($p < 0.05$).

The gender differences in the lower limb kinematic data of male and female badminton players at the moment of initial contact of the badminton landing task are shown in **Table 1**.

At the moment of initial contact during the post-landing impact phase of the single-leg landing task in badminton, the knee valgus angle differed significantly between males and females, being 6.27 ± 2.54 in females and 1.84 ± 3.28 in males ($p < 0.05$). Other than that, there were no significant gender differences between the other joint angles. Another point worth noting is that although there was no significant gender difference in the ankle adduction angle at the moment of initial contact, female badminton players had 8.6 degrees more adduction angle than males.

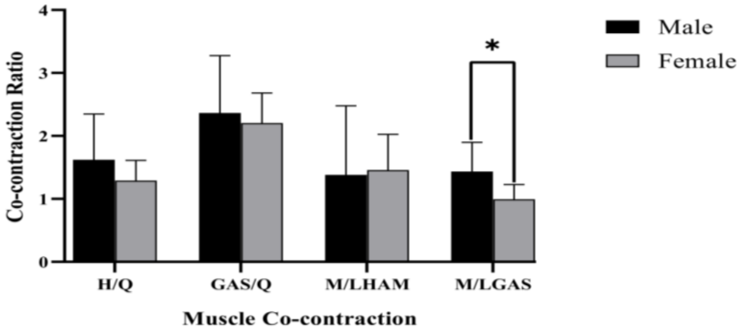

Figure 4. Badminton single-leg landing task, mean and standard deviation of lower limb muscle co-contraction activity ratio during the post-landing impact phase.
* Represents statistically significant differences.

Table 1. Means and standard deviations (degrees) of hip-knee-ankle joint angles at the moment of initial contact in the badminton single-leg landing task.

Variables	Male	Female	*p* Value
Hip			
Flexion(+)/extension(−)	10.86 ± 7.96	10.02 ± 8.61	0.8423
Abduction(+)/adduction(−)	36.33 ± 4.25	39.88 ± 5.84	0.1864
External(+)/internal rotation(−)	15.56 ± 5.59	17.43 ± 5.52	0.5446
Knee			
Flexion(+)/extension(−)	18.92 ± 6.93	17.47 ± 6.56	0.6751
Valgus(+)/varus(−)	1.84 ± 3.28	6.27 ± 2.54	0.0091*
External(+)/internal rotation(−)	−4.42 ± 4.51	−0.61 ± 3.42	0.0915
Ankle			
Dorsiflexion(+)/plantar flexion(−)	−42.81 ± 8.80	−35.81 ± 6.91	0.0985
Eversion(+)/inversion(−)	0.14 ± 3.49	−0.40 ± 4.41	0.8168
Abduction(+)/adduction(−)	17.39 ± 3.38	25.99 ± 10.71	0.0835

* Represents statistically significant differences.

The mean and standard deviation (in degrees) of the hip-knee-ankle joint angles at the peak moment after GRF in the badminton single-leg landing task are shown in **Table 2**.

During the post-landing impact phase of the single-leg landing task in badminton, the mean angle of flexion was 7 degrees smaller in females than in males at the moment of posterior peak GRF, and there was a significant difference between males and females ($p < 0.05$). At the moment of posterior peak GRF, the mean knee valgus angle was 5 degrees greater in females than in males, with a highly significant difference between males and females ($p < 0.05$). In addition, the mean ankle plantarflexion angle was 9 degrees greater in males than in females at the moment of posterior peak GRF, with a significant difference between males and females ($p < 0.05$). It is also worth noting that although there was no significant gender difference in ankle adduction angle, the adduction angle of female badminton players at the moment of posterior peak GRF was 6 degrees greater than that of males.

Table 2. Means and standard deviations (degrees) of hip-knee-ankle joint angles at the moment of posterior peak GRF in the single-leg landing task in badminton.

	Male	**Female**	***p* Value**
Hip			
Flexion(+)/extension(−)	15.27 ± 5.36	18.25 ± 3.93	0.2846
Abduction(+)/adduction(−)	36.25 ± 4.57	39.83 ± 5.56	0.1810
Internal(+)/external rotation(−)	15.31 ± 4.81	14.87 ± 6.11	0.8824
Knee			
Flexion(+)/extension(−)	23.90 ± 5.04	16.71 ± 4.20	0.0229*
Valgus(+)/varus(−)	0.88 ± 2.59	6.16 ± 2.83	0.0024*
Internal(+)/external rotation(−)	−4.60 ± 4.29	0.12 ± 4.36	0.0730
Ankle			
Dorsiflexion(+)/plantar flexion(−)	−37.05 ± 7.17	−28.34 ± 5.60	0.0250*
Eversion(+)/ Inversion(−)	1.17 ± 3.39	0.19 ± 4.76	0.6835
Adduction(+)/abduction(−)	18.47 ± 4.01	24.89 ± 7.78	0.0608

* Represents the presence of significant differences.

5. Discussion

The experimental results supported our hypothesis, confirming significant gender differences in lower limb neuromuscular control among badminton players during single-leg landing. Females displayed smaller knee flexion and ankle plantarflexion, larger knee valgus landing patterns, larger rectus femoris, medial hamstrings, and gastrocnemius muscle activity patterns compared to males. They also exhibited smaller co-activation patterns of medial and lateral gastrocnemius muscles during the landing impact phase.

Our study revealed a gender-biased movement pattern in the lower limbs of badminton players during a high-risk single-leg landing task. Specifically, females had smaller knee flexion angles at the moment of posterior peak GRF, which is considered a risk factor for ACL injury [27]. Video analysis of non-contact ACL injuries has shown a more extended knee landing position, associated with smaller knee flexion angles [28]. Smaller knee flexion angles have been associated with larger ACL elevation angles, leading to greater strain on the ACL [29]. Studies have consistently demonstrated that smaller knee angles during various landing, jumping, and lateral cutting tasks result in higher ground reaction forces and quadriceps loading forces [30]. Moreover, smaller knee angles are linked to increased anterior tibial shear forces and are predicted to increase ACL loading during single-leg landing tasks [31]. Therefore, it is widely accepted that small knee flexion angles during landings are detrimental to ACL injury prevention.

Furthermore, our study found that female badminton players exhibited greater knee valgus angles at both initial contact and posterior peak GRF moments. This aligns with previous research showing that large valgus angles are associated with ACL injuries [8,32]. Observations of ACL injury videos, cadaver studies, and prospective studies on athletes have consistently shown that large knee valgus angles predict a higher risk of ACL injury. Additionally, a study specifically focusing on female badminton players revealed greater knee valgus angles during high-risk landing tasks compared to low-risk single-leg landing tasks [33]. This substantial body of evidence supports the belief that large valgus angles increase the risk of ACL injury in females. Additionally, female badminton players exhibited smaller ankle plantar flexion angles at the moment of peak GRF. Previous studies have indicated that a too-small plantarflexion angle is associated with inadequate absorption of ground reaction forces by the gastrocnemius muscle during landing. This can result in impact forces directly affecting the knee joint, potentially increasing the risk of ACL injury [27]. However, our findings differ slightly from previous studies [32,34], which may be attributed to the inclusion of a shuttlecock in our experimental design. Previous research has shown that the presence or absence of a ball can influence the biomechanical patterns of the lower limb [10,35]. Furthermore, while there was no significant gender difference in ankle adduction angle, females had a greater adduction angle than males at both initial contact and peak GRF. This difference may be related to variability in flexibility between males and females but may not directly impact ACL injury risk [36].

During the impact phase, female badminton players exhibited greater rectus femoris muscle activity compared to males, consistent with previous findings [37,38]. Increased rectus femoris activation is associated with a higher risk of ACL injury. The contraction of the rectus femoris muscle, connected to the anterior aspect of the proximal tibia through the patellar ligament, increases stress on the ACL when the knee joint angle is smaller [31]. Studies have shown that rectus femoris activation contributes to ACL loading and proximal tibial anterior shear force. In our study, both males and females exhibited smaller knee flexion angles at the moment of posterior peak GRF, with females having greater knee extension force arms. This, combined with the greater activation of the rectus femoris in females, may have resulted in a higher ACL load and increased ACL injury risk in females.

Female badminton players also displayed greater medial hamstring activity than males during the post-landing impact phase, consistent with previous studies [12]. The reasons for this increased activity may be attributed to gender differences in factors such as knee valgus angles, trunk frontal plane position asymmetry, or medial-lateral muscle balance. While the hamstrings play a role in providing posterior tibial forces and are generally considered beneficial in ACL protection, isolated hamstring contractions have minimal effect on ACL forces. The effectiveness of hamstring quadriceps co-contraction in protecting the ACL is limited to knee flexion angles greater than 22–30 degrees [13]. In our study, despite greater hamstring activity in females, the landing angle for females was typically less than 20 degrees. Therefore, the large activity of the medial hamstrings at the moment of posterior peak GRF may provide limited protection for the ACL.

During the post-landing impact phase, female badminton players exhibited greater activity in the medial and lateral gastrocnemius muscles compared to males. Previous studies have reported this gender difference in neuromuscular control during landing tasks [14]. The contraction of the gastrocnemius muscle has been associated with injury risk factors in the anterior cruciate ligament (ACL) based on models and in vivo studies [39]. The gastrocnemius was found to contribute significantly to peak tibial anterior shear force, which can increase ACL stress [39]. Activation of the gastrocnemius has been shown to increase tibial anterior displacement, potentially acting as an antagonist to the ACL [40]. This association may be due to the gastrocnemius' location and its ability to generate compressive forces, leading to increased anterior shear forces and displacement of the tibia. On the other hand, some arguments suggest that gastrocnemius activity plays a protective role in the ACL [41]. Studies have shown that increased gastrocnemius muscle strength is associated with a decrease in stress on the tibial anterior shear or ACL. The variability in co-contraction of the medial and lateral gastrocnemius muscles was also observed, with females showing a smaller ratio of co-activation compared to males. The co-contraction of these muscles helps to balance varus and valgus moments, maintaining frontal plane stability. The greater co-contraction ratio in males may assist in preventing greater valgus loads and angles, contributing to knee stability and potentially reducing the risk of ACL injuries [42].

A recent study revealed that female badminton players exhibit a larger knee valgus angle compared to their male counterparts during the landing preparation phase of a single-leg landing task in badminton. This increased angle may heighten their susceptibility to anterior cruciate ligament (ACL) injuries [20]. Furthermore, the study observed that female athletes demonstrated heightened muscular activity in the gluteus maximus, rectus femoris, and medial gastrocnemius during the landing preparation, which could be linked to the larger knee valgus angle. Another investigation demonstrated that an 8-week neuromuscular training program successfully reduced the knee valgus angle and enhanced the co-activation patterns of specific lower limb muscles, This finding indicates that neuromuscular training might serve as an effective strategy to mitigate knee valgus by bolstering muscle co-activation, which could, in turn, lower the risk of ACL injuries. A separate study assessed the impact of integrated neuromuscular training (INT) on the prevention of sports injuries and enhancement of athletic performance among professional female badminton players, The findings indicated that an 8-week INT regimen was instrumental in ameliorating limb asymmetry [43], averting sports injuries, and elevating the performance levels of these athletes. Concurring with the previous study [44], another research concluded that integrated neuromuscular training was efficacious in alleviating limb asymmetry, preventing sports injuries, and augmenting the performance of female badminton players. Based on our findings, neuromuscular training programs targeting knee valgus reduction and promoting gastrocnemius co-contraction stability should be prioritized for female badminton players [44].

In summary, our study identified gender differences in neuromuscular control during the landing preparation phase of the badminton single-leg landing task. However, there are limitations in the data collection processes, including EMG and 3D motion analysis, which can affect the results [45]. This study is among the first to examine sex-specific neuromuscular differences during a high-risk badminton-specific movement, filling an important gap in the literature. Additionally, the study was conducted in a controlled laboratory setting, which may not fully replicate the ACL injury risk in actual matches. Future studies should explore larger, more diverse samples and evaluate the efficacy of targeted training interventions to address these neuromuscular differences.

6. Conclusion

There were significant gender differences in neuromuscular control (muscle activity patterns, movement patterns) between badminton players during the impact phase of the badminton single-leg landing task. The neuromuscular control strategies exhibited by female badminton players may be inadequate for ACL protection and may be a potential risk factor for a high incidence of ACL injury.

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