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Article

Pre- or co-activation of leg muscles is associated with risk of non-contact knee injury during a single-leg landing in badminton

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Abstract: Objectives: The present study evaluated if lower limb muscle pre- and co-activation was associated with the biomechanics of knee joint control during backward step single-leg landings following a badminton overhead stroke. **Methods:** Three-dimensional biomechanics data of the knee joint and electromyographic data of lower limb muscles were collected from 34 badminton players. Linear regression analysis of gluteus maximus, quadriceps, hamstrings, gastrocnemius pre-and muscle co-activation in relation to peak knee flexion angle, knee valgus angle and moment, peak extension moment, and tibial anterior shear force in participants 100 ms before initial touchdown were analyzed. **Results:** Increased quadriceps pre-activation predicts increased knee valgus angle (R^2 = 0.48, P < 0.001). Greater Lateral Hamstring/Quadriceps co-contraction predicts increased peak knee extension moment (R^2 = 0.39, P < 0.001). Greater lateral gastrocnemius/quadriceps co-contraction predicts an increased peak knee valgus moment (R^2 = 0.20, P = 0.0073). No EMG pre-activity parameters were predictors (P > 0.05) for knee flexion angle and anterior tibial shear force. **Conclusion:** These findings suggested that pre-activation of the quadriceps or co-contraction ratio of the lateral hamstrings to the quadriceps or lateral gastrocnemius to the quadriceps would be positively associated with the risk of non-contact anterior cruciate ligament (ACL) injuries during a single-leg landing following a badminton backward step overhead stroke.

Keywords: muscle pre- and co-activation; ACL injuries; kinematics; kinetics

1. Introduction

Badminton is a non-contact racket sport that was included in the Olympic program in 1992 and has since attracted approximately 200 million enthusiasts, making it one of the most popular sports worldwide [1]. The sport demands a high level of physical agility, including jumps, lunges, rapid changes in direction, and sudden stops. These movements place significant stress on the lower limbs, enlarging the risk of joint injuries [2,3]. Among these, due to the nature of badminton, contact-related injuries are relatively rare, non-contact ACL injuries are particularly serious and prevalent [4]. Statistics indicate that over 200,000 people suffer from ACL injuries annually, with approximately 80% of these injuries classified as non-contact [5]. Such injuries can lead to prolonged absences from competition, threatening their careers, impose a significant economic burden and substantially increasing the risk of early-onset osteoarthritis [6]. An important aspect of protecting both amateur and professional athletes is injury prevention. For decades, researchers have worked to identify modifiable risk factors and develop and implement interventions aimed at minimizing or eliminating these factors. Observational studies have identified that most non-contact ACL injuries occur during lateral rotation, landing, and deceleration maneuvers in various sports [7]. In the context of badminton, Kimura et al. demonstrated that the most common ACL injuries occur during single-leg landings following an overhead backhand stroke, particularly affecting the knee opposite to the racket hand [8].

Researchers have extensively explored the factors that may contribute to anterior cruciate ligament injuries. The majority of researchers have suggested that the underlying causes are multifactorial in nature, encompassing a combination of anatomical characteristics, genetic predispositions, and factors related to neuromuscular control [9]. Given that the kinematics and moments of the joint are regulated by the surrounding neuromuscular tissues, there is increasing evidence that inadequate neuromuscular control during potentially hazardous maneuvers is a key factor in ACL injuries [10,11]. The primary contributors to ACL loading include significant tibial shear forces, as well as extension, valgus angle and moments at the knee joint [12]. The quadriceps are generally considered antagonists to the ACL [13]. Connected to the proximal tibia via the patellar tendon, quadriceps contraction at low knee flexion angles increases anterior translation of the tibia relative to the femur, thereby elevating the stress and strain on the ACL. In addition, over-activation of the quadriceps or under-activation of the hamstrings may lead to excessive valgus angles and extension moments [14]. This suggests that evaluating muscle pre-activation characteristics during landing may be effective for developing strategies for minimizing the risk of ACL injury.

Muscle pre-activation is a common response during jumping or landing [15]. During activities such as rotation, jumping, or falling during landing, the body is expected to endure significant impact forces. To recover from perturbations experienced during movement, the body activates muscles to regulate the stability and function of the weight-bearing limbs. Research on human landing mechanics has demonstrated that the pre-activation of limb muscles is a critical component of neuromuscular control strategies for ensuring safe landings [16,17]. Assessing muscle activation patterns can help evaluate dynamical control of joint stability during motor tasks that affect the joint loading [18]. Generally, muscle activation occurring before foot contact with the ground (i.e., pre-activation) is controlled by the central nervous system. It is believed that increased muscle pre-activation, particularly in the calf muscles, is a result of heightened muscle tension [19]. There have been a variety of studies that have established significant associations between muscle activation patterns and knee biomechanics [20–22]. An increased quadriceps pre-activation has been linked to higher maximal anterior tibial shear forces and reduced knee flexion moments, while greater lateral hamstring pre-activation has been associated with decreased maximal knee flexion angles [23]. In addition, significant correlations have been observed between gluteal and hamstring activation levels and peak knee frontal projection angles [24]. Leg muscles are selectively activated to resist external loads applied to the knee during pre-planned single-leg lateral cuts [25]. ACL injury prevention programs emphasize the importance of training quadriceps/hamstring (Q/H) co-activation to limit excessive tibial translation and protect the ACL [26,27]. While many research have provided valuable insights into common ACL injury mechanisms with muscle activation patterns [12,28], there is still a significant gap in understanding the specific characteristics of knee muscle activation in the context of landing following a badminton overhead stroke performance.

In summary, as ACL injuries occur rapidly after ground contact, how the lower limb muscles is activated prior to landing can influence injury risk [29], given that the relationship between muscle pre-activation and muscle co-contraction characteristics and knee joint biomechanics may vary across different physical tasks, and that the connection between leg muscle activity and ACL injury factors during high-risk maneuvers in badminton remains unclear, The main objective of the present study was to investigate whether the pre- or co-activation patterns of lower limb muscles were key factors in predicting the performance variations of knee joint biomechanics during a single-leg landing after a badminton backhand overhead shot.

2. Methods

2.1. Participants

All participants were members of Jeonbuk University badminton teams, for standardized testing, all participants were right-handed dominant and were free from any physical discomfort prior to testing. The following inclusion criteria were met by all participants recruited: (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; (3) participants had to participate in organized training, at least four times a week, with each session lasting a minimum of two hours. Participants were excluded if they had: (1) a history of previous knee injury or surgery, (2) any recent injury to the lower extremity (previous 6 months). The study received approval from the Jeonbuk National University Ethics Committee (JBNU2022-01-004-002). Before participating, all participants were informed of the experimental procedures and potential risks, and they provided written informed consent.

2.2. Prepare for testing

Each participant was equipped with 57 14-mm reflective Marker points for whole-body bone marking. Kinematic data were also collected using a motion capture analysis system with 13 high-speed infrared cameras (Prime 17W, OptiTrack, NaturalPoint, Inc, Corvallis, OR, USA) at a sampling frequency of 120 HZ.

A floor-embedded force platform (OR6-6-2000 force Platform, AMTI Inc. Plano, TX, USA) was used to collect ground reaction force (GRF) data at a sampling frequency of 1200 HZ with a maximum delay time of 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.

Prior to each experiment, kinematic, force platform, and EMG data were synchronized through a 3D motion capture system, MotiveBody 2.2.0 software (OptiTrack, LEYARD, Buffalo Grove, IL, USA).

Surface EMGs of gluteus maximus (GMAX), quadriceps femoris (QF), lateral hamstrings (LH), medial hamstrings (MH), medial gastrocnemius (MG), and lateral gastrocnemius (LG) were selected, and the location of EMGs affixed to each muscle, as well as the mode of testing maximal voluntary isometric contraction (MVIC), was tested (as shown in **Table 1**). Maximal voluntary isometric contractions were performed for each muscle for 5 S in the following manner.

Before attaching the myoelectrics, the skin surface was shaved and cleaned with alcohol, and after drying the skin, they were attached to the upper part of the muscle belly parallel to the muscle fibers and fixed with motion tape to reduce motion artifacts [30].

Badminton balls were sent to the designated area under the same condition using a Fung Choi SPT6000 badminton ball launcher (SPTLOOKER, Guangzhou, China). Participants wore uniform sportswear, individual socks and shoes, and used a uniform racket for overhead backhand strokes.

Table 1. Muscle name, EMG placement, and testing position and action for maximal voluntary isometric contraction (MVIC) testing.

Muscle	Electrode Site	Position	MVC Test Maneuver
Gluteus maxim (GMAX)	Lateral 80% of the line between the midpoint of the sacrum and the greater trochanter of the femur.	Prone	The stretch strap is fixed to the posterior side of the distal thigh and hip extension is performed with the knee in 90 degrees of flexion.
Quadriceps femoris (QF)	Upper 40% of the line between the superior patella and the anterior superior iliac spine.	Sitting	Knee flexion at 90 degrees, the stretch strap is fixed on the anterior side of the distal lower leg, perform knee extension.
Medial hamstrings (MH)	Lower 80% of the line of the ischial tuberosity with the medial popliteal crease.	Prone	Knee flexion 45 degrees, the stretch strap is fixed on the back of the distal lower leg, internal rotation of the lower leg and perform knee flexion.
Lateral hamstrings (LH)	Lower 80% of the line of the ischial tuberosity to the lateral popliteal crease.	Prone	Knee flexion 45 degrees, the stretch strap is fixed on the back of the distal lower leg, external rotation of the lower leg and perform knee flexion.
Medial gastrocnemius (MG)	Upper 85% of the medial Achilles tendon in line with the medial popliteal crease	Prone	Knee extension, stretch strap fixed on the forefoot, internal rotation of the lower leg and perform plantarflexion.
Lateral gastrocnemius (LG)	Upper 85% of the line connecting the lateral Achilles tendon to the lateral popliteal crease	Prone	Knee extension, stretch strap fixed on the forefoot, external rotation of the lower leg and perform plantarflexion.

2.3. Test procedures

Each participant performed a 10-minute warm-up routine, which included jogging and stretching exercises, before the formal experiment. The task involved executing a single-leg landing following a backhand overhead shot. To minimize individual variations in movement, an experienced badminton coach demonstrated the correct movements and footwork to each Participant. A 45° indicator mark was placed on the badminton court to guide the participants. Starting from the initial position, the participants stepped back with their left foot towards the left, following the indicator mark in the backcourt, executed a backhand shot with their right hand, and then landed on the force plate with their left leg before quickly returning to the starting position (as illustrated in **Figure 1**). After a few practice trials, each participant performed three to five formal trials, with a 30-second rest between each trial to prevent fatigue.

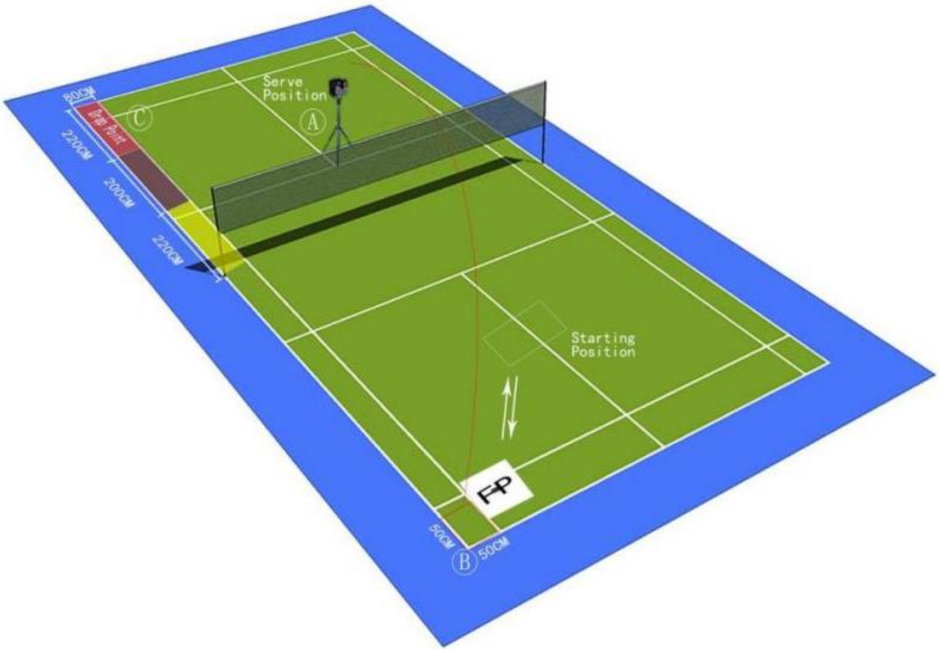


Figure 1. Laboratory setup: F-P and A represent the positions of the force platform and shuttlecock launcher, respectively. The shuttlecock launcher sends shuttlecocks to the 50 cm × 50 cm area marked as B. The red curved line depicts the trajectory of the shuttlecock. Participants start from the starting point, move their left foot diagonally backward, then jump with their right foot to execute a backhand smash motion. After landing on the force platform with their left foot, they quickly return to the starting position. Area C indicates the landing point of the shuttlecock after being hit.

2.4. Data processing and analysis

The 100 MS before the initial contact (IC) with the force plate is thought to reflect the pre-activation state of the muscles before landing [31]. Therefore, we mainly processed and analyzed the muscle activity and muscle synergistic contractile activity in this phase. The first touchdown (IC) was defined as the first frame in which the force plate data exceeded 10 N.

Upon completion of the experiments, the kinematic data were processed using Visual 3D software (Professional 6.0, C-Motion Inc, Germantown, MD, USA). Degrees of freedom were defined, and the acquired 3D marker trajectories were processed to derive the lower limb joint rotation data for each time frame. The pelvis, hip, knee, ankle, and joint centers, along with local segment coordinate systems, were defined following established protocols [32,33]. The knee angle was determined as the position of the calf relative to the thigh, using the following axes: X (flexion/extension), Y (adduction/abduction), and Z (internal/external rotation). The direction of positive angles was determined according to the segmental coordinate system of the reference segment and was defined based on the right-hand rule. The directions were standardized as follows: flexion was positive, extension was negative; adduction was positive, abduction was negative; internal rotation was positive, external rotation was negative. Joint moments were calculated using the inverse dynamics method, which integrated force plate data, kinematic data, and segmental inertia parameters.

The electromyographic (EMG) pre- and co-activation data were analyzed using the EMG works provided with the EMG acquisition system (Trigno Avanti Sensor, Delsys, USA). The signals were first filtered using a fourth-order Butterworth bandpass filter with a frequency range of 10–400 Hz. Subsequently, the EMG signals were processed with a 20-ms root-mean-square (RMS) correction, utilizing a window size of 0.04 seconds and a 0.02-second overlap between consecutive windows. To determine the pre-activation phase preceding each landing, the mean RMS amplitude was calculated for each muscle over three trials and then normalized according to the normalized RMS of the maximum voluntary isometric contraction (MVIC). Simultaneous RMS pre-activation of the medial hamstring/quadriceps (ML/Q), lateral hamstring/quadriceps (LH/Q), medial gastrocnemius /quadriceps (MG/Q), lateral gastrocnemius /quadriceps(LG/Q) was used to calculate a muscle co-contraction ratio with a formula previously reported by Rudolph et al. [34]. Respectively, the mean values for each biomechanical variable associated with the pre-activation phase of the badminton landing task were computed. Kinetic variables were normalized to the Participant's body weight (kg^{-1}), and torques were normalized to the product of the Participant's body weight and height ($kg^{-1} \times m^{-1}$).

Linear regression analyses were conducted using SPSS version 21.0 (SPSS Inc., Chicago, IL) to identify which muscle pre-activation and co-contraction significantly predict knee kinematic and kinetic outcomes, which are considered to influence the risk of anterior cruciate ligament (ACL) injury. The variables for pre-activation and co-activation of lower limb muscles include: GMAX, QF, MH, LH, MG, LG, MG/Q, LG/Q, MH/Q, and LH/Q. The knee biomechanics variables include knee flexion angle, valgus angle and moment, peak extension moment, and proximal tibial anterior shear. An alpha level of 0.05 was selected to determine if predictor variables would be included in the final equation and for determining the significance of the model in predicting the response variable.

3. Results

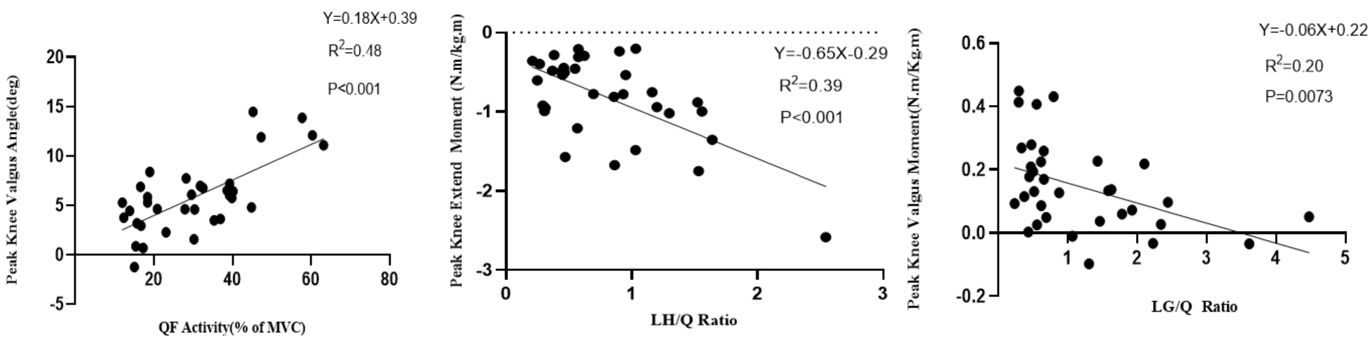
Table 2 was the characteristics of participants. For the present study, GPower 3.1 software was used with $a = 0.05$, 95% statistic and effect of 0.4. A minimum of 30 participants were required, therefore, 34 experienced badminton players were recruited.

Table 2. Characteristics of participants (means and standard).

Gender	Age (years)	Height (m)	Weight (kg)	Years of training
Males (N = 17)	20.63 ± 0.92	1.78 ± 0.03	71.63 ± 9.97	10.38 (± 1.69)
Females (N = 17)	21.5 ± 2.45	1.67 ± 0.05	59.50 ± 9.97	11.88 (± 3.18)

Figure 2 illustrates the relationship between lower limb muscle pre- and co-contraction with knee biomechanical variables during landing in badminton players. Increased quadriceps pre-activation predicts increased knee valgus angle ($R^2 = 0.48$, $p < 0.001$). Greater lateral hamstring/quadriceps Co-Contraction predicts increased peak knee extension moment ($R^2 = 0.39$, $p < 0.001$). Greater lateral gastrocnemius and

quadriceps co-contraction predicts increased peak knee valgus moment ($R^2 = 0.20$, $P = 0.0073$). No EMG pre-activity parameters were predictors ($P > 0.05$) for knee flexion angle and anterior tibial shear force.



(a) **(b)** **(c)**

Figure 2. Relationship between **(a)** knee joint varus angle and quadriceps femoris pre-activation, **(b)** knee joint peak extension torque and LH/Q ratio, **(c)** knee valgus peak moment and LG/Q ratio during landing in badminton players.

4. Discussion

In this study, evaluated if lower limb muscle pre- or co-activations predicted the likelihood of ACL injury during a single-leg landing task following a backhand overhead shot in badminton players. The results from the present study indicated that increased quadriceps pre-activation predicted a greater knee valgus angle, while a higher hamstring/quadriceps co-contraction ratio predicted a greater knee extension moment and a higher gastrocnemius/quadriceps co-contraction ratio predicted a greater knee valgus moment. These findings partially support our hypothesis and suggested that lower limb muscle pre- or co-activations during the single-leg landing would be a notable factor in predicting the risk of non-contact ACL injury among competitive badminton players.

The present study suggested that quadriceps pre-activation predicted 48% likelihood of peak knee valgus angle during landing. Observations from ACL injury videos, cadaveric studies, and prospective research on athletes consistently indicate that excessive knee valgus angles are predictive of a higher risk of ACL injury. Knee valgus can result from either abduction of the distal tibia relative to the femur or rotational motion of the knee in the transverse plane [33], both of which are considered risk factors for non-contact ACL injury [35]. Muscle activation is a key determinant of muscle strength and, in this study, greater quadriceps pre-activation enhances quadriceps strength, which may contribute to larger valgus angles. Knee valgus affects knee valgus torque, which can increase tibial migration and impose substantial loads on the ACL [36]. Elevated valgus loading has been shown to heighten ACL tension [37], indicating that an increased valgus angle could be a significant factor in the mechanism leading to ACL rupture in athletes. Observations from ACL injury videos, physical assessments, and prospective studies have consistently demonstrated that greater knee valgus angles correlate with a higher risk of ACL injury [8,28]. Overall, poor leg alignment and excessive knee valgus (i.e., medial movement of the knee in the frontal plane during activity) impose additional structural loads on the musculoskeletal system, potentially leading to knee overuse [38]. This finding aligns with previous research suggesting that increased quadriceps activation during landing preparation may have elevated ACL loading [39].

The results from the present study demonstrated that greater coactivation of the lateral hamstring/quadriceps (LH/Q) ratio was associated with increased knee extension moments. This is similar to Becky L.'s research, which suggests that the LH/Q ratio may be related to knee forces and ACL loading during landing [40]. The protective effect of hamstring-quadriceps co-contraction against ACL injuries is limited to knee flexion angles greater than 22–30 degrees [41]. Elevated LH/Q coactivation could potentially increase ACL strain, thereby raising the risk of ACL injury. In the sagittal plane, the hamstrings are the primary muscle group responsible for generating posterior force on the tibia. Imbalanced or poorly coordinated hamstring-to-quadriceps activation patterns may lead to translational motion of the tibia relative to the femur, potentially contributing to knee overuse injuries [42]. Neuromuscular contraction plays a crucial role in maintaining body balance and stability. During the early stages of landing, when impact forces are high, internal muscle contractions must generate sufficient extension moments to counteract the flexion moments produced by external forces and control the body's center of gravity. The quadriceps, in particular, is a major contributor to the extension moment. Poor neuromuscular control may lead to an overreliance on greater extension moments generated by quadriceps activation to maintain equilibrium. Increased extension moments are associated with enhanced anterolateral knee strength, which may result in increased loading on the anterior cruciate ligament. However, it is important to note that while greater extension moments are a determinant of increased anterior tibial force, this does not imply that high quadriceps activation solely dictates anterior tibial shear force, as other factors (e.g., angulation) also play a role [43]. Therefore, reducing the LH/Q coactivation ratio may help mitigate the risk of ACL injuries.

In the present study, greater LG/Q co-activation was associated with higher peak knee valgus moments, which was similar to Mengarelli's research [43]. During dynamic cutting and pivoting movements, the load on the muscles responsible for external rotation and valgus torque at the knee increases. However, co-activation and pre-activation can stabilize the knee joint, enabling effective directional changes during running. The present study may have underestimated the importance of the gastrocnemius, as both the gastrocnemius and quadriceps are primary antagonists (i.e., load bearers) of the ACL and the primary groups causing the anteriorly directed tibia force at the first peak in ACL force. According to modeling and in vivo studies, gastrocnemius contraction is associated with the risk of ACL injury. Through its flexor activity, the gastrocnemius exerts an influence on the knee joint. When co-activated with the quadriceps, this leads to greater strain on the knee ligaments. Some studies have indicated that increased valgus moments result in higher ACL loading and was also an important mechanism affecting ACL injury [44,45]. An increase in valgus moment does not necessarily indicate that injury occurs solely in the frontal plane; it may be the result of a combined multi-plane effect. When badminton players were landing, the increase in anterior tibial force caused by the co-contraction of the lateral gastrocnemius/quadriceps may lead to an increase in valgus moment due to this multi-plane interaction. In this case, reducing the co-contraction of the LG and Q may help decrease the incidence of ACL injury.

The present study acknowledges several limitations. EMG signals are complex and can be influenced by individual characteristics during data acquisition. Additionally, errors in V3D model measurements, such as those arising from marker placement, skin motion artifacts, joint center definition, and leg length discrepancies, may impact kinematic results [46]. While our study identified correlations between lower limb muscle pre-activation and knee kinematics and kinetic variables, these correlations do not imply causation. It is important to note that lower limb muscle activity may not directly lead to changes in knee joint kinematics or kinetics during a one-legged badminton landing. Furthermore, the biomechanical properties of the knee joint can be influenced by various factors, including the interactions between the arms, trunk, pelvis, thighs, calves, and feet during landing tasks. Our study focused solely on the relationship between knee muscle activity and knee biomechanical factors during the preparatory phase. However, deficits in neuromuscular control across different body components may contribute to suboptimal movement patterns, potentially increasing the risk of ACL injury [47,48]. To enhance our understanding of knee biomechanics and the role of neuromuscular activation, future research should consider exploring the effects of trunk muscles on knee kinematics. Investigating additional neuromuscular activation patterns and their impact on dynamic knee control could provide valuable insights into the complex factors influencing knee joint biomechanics. Additionally, this study was conducted in a controlled laboratory setting, which may not fully replicate real-game scenarios where ACL injuries are influenced by multiple factors. Consequently, there may be differences compared to actual competition conditions.

Despite these limitations, this study represents the preliminary investigation about the relationship between lower limb muscle pre-and co-activation and knee biomechanics during high-risk badminton maneuvers. This study fills a research gap by investigating the role of lower limb muscle pre-activation and co-activation in predicting risk factors for ACL injuries during high-risk badminton maneuvers. Based on our findings, we recommend that future protocols for the prevention of non-contact ACL injury should emphasize optimizing neuromuscular control, particularly during the landing preparation phase.

5. Conclusion

The present study confirmed the lower limb muscle pre- or co-activation predicted the likelihood of ACL injury during single-leg landing during a badminton stroke. Reducing quadriceps pre-activation, lateral hamstring/quadriceps (LH/Q) co-contraction ratio and lateral gastrocnemius/quadriceps (LG/Q) co-contraction ratio may help prevent ACL injury. These findings could provide valuable insights for developing effective ACL injury prevention programs.

Author contributions: Conceptualization, YX and HMC; methodology, YX, SK and TW; software, ZH and TW; validation, HMC and SK; formal analysis, YX and TW; investigation, YX, HMC and ZH; resources, SK; data curation, SK; writing—original draft preparation, YX, HMC and ZH; writing—review and editing, SK and TW; visualization, TW; supervision, SK; project administration, HMC. All authors have

read and agreed to the published version of the manuscript.

Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Jeonbuk National University (protocol code JBNU2022-04-008-002). Informed consent was obtained from all subjects involved in the study.

Statements and declarations: The authors affirm that they have no relationships or financial interests that might appear to conflict with the work described in this paper.

Data availability: Derived data supporting the findings of this study are available from the corresponding author on request.

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

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