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Original Article

Association between Preparatory Knee Muscle Activation and Knee Valgus Angle during Single Leg Cross Drop Landing Following Anterior Cruciate Ligament Reconstruction

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ABSTRACT

Background: Knee valgus angle seems to be a key factor in both primary– and second–ACL injury risk models. The control of the alignment of the lower limb during dynamic movements depends on the neural activation of the muscles crossing the knee joint prior to the occurrence of stressful events. The current study examined the relationship between the preparatory knee muscle activity and knee valgus angle.
Methods: Twenty-eight ACL reconstructed (ACLR) athletes were asked to perform three trials of a single-leg cross drop landing (SCD). Lower extremity kinematics and surface EMG were recorded. Initial contact knee valgus angle and EMG from 100 ms prior to ground contact were used in the data analyses.
Results: Preparatory activation medial and lateral hamstring muscles were found to be negatively correlated with knee valgus angle at initial contact ($P<0.05$). However, the preparatory activity of vastus medialis and vastus lateralis muscles was not associated with initial contact knee valgus angle ($P>0.05$).
Conclusion: The preparatory activity of the knee muscles is linked to knee valgus angle at initial contact, and it may indicate a potential target of second ACL injury prevention programs.

Introduction

More than 130,000 people experience an anterior cruciate ligament reconstruction (ACLR) in the United States annually [1]. Most orthopedic surgeons advocate surgical reconstruction of ACL-deficient athletes who expect to return to sports participation after an ACL injury. Only 65% of athletes could resume their pre-injury level of the sport [2]. It is estimated that young athletes who successfully return to activity are at approximately 30 to 40 times greater risk of sustaining a second knee injury [3]. Aside from the increased risk of a second injury, patients after ACLR have an increased risk of developing early onset of osteoarthritis (OA) [4]. In spite of the improvement in post-operative ACLR rehabilitation protocols, muscle weakness [5], impaired movements [6], abnormal neuromuscular control [7], and difficulty in returning to activity [8] are common for many years after ACLR. These factors place the athletes at a significantly higher risk for second ACL injury [3].

Abnormal neuromuscular and biomechanical patterns are generally persistent up to 2 years after ACLR [6, 7] and may help describe the high incidence of the second ACL injury. Altered lower limb joint mechanics in sagittal and frontal plane are usually detected after ACL reconstruction during dynamic exercises, and these alterations have been considered serious risk factors for second ACL injury [7]. Paterno et al. found that participants who experienced a second ACL injury had diminished hip external rotator moment, asymmetry in

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sagittal plane knee moments, and increased knee valgus angle during a bilateral drop vertical jump task [7]. These findings show that hip and knee positioning are strong predictors of a second ACL injury and emphasize the importance of thorough assessment and understanding of biomechanics during high-demand activities following ACLR [9]. Knee joint valgus has been related to primary and secondary ACL injury risk [7, 10]. Valgus loading can increase relative ACL strain and may reach levels high enough to cause ligamentous failure [11]. Minimizing knee valgus during sports exercises may be essential for reducing the incidence of ACL injury. Proper lower limb alignment enables the confronted forces to be well-transferred to the joints [12].

Much similar to primary ACL injuries, the greater part of secondary ACL injuries is caused by noncontact mechanisms, highlighting altered intrinsic neuromuscular control as a key factor in injury risk [2]. In addition to biomechanical modifications, adaptations in muscle activity are also commonly seen during dynamic exercises after ACL reconstruction [13]. Gokeler et al. assess the bilateral lower limb joint kinematics and kinetics and onset time of EMG activity during the single leg hop test in ACL-reconstructed patients [13]. They found that muscle onset times of the involved limb were significantly earlier before landing. This indicates that patients, unconsciously or consciously, increase the pre-tension of the limb muscles before the landing of a single leg hop test [10]. Deficits in the neuromuscular control following ACLR may not be necessarily a result of the primary knee injury and following surgery, but may also depict the athlete’s pre-injury movement patterns [14, 15]. Deficits in neuromuscular function and dynamic strength, as well as the inhibition of muscular exertion may establish a condition where the muscles cannot absorb the requisite loading, and subsequently, prepare the joint for ground contact that supplies a proper lower extremity alignment. This may lead to compensatory movement patterns in lower limb joints on the reconstructed limb that result in altered kinematics and kinetics [12]. In dynamic movements, the foremost function of the muscle is to stabilize the joints by generating force [13]. To limit frontal plane motion, it is important to notice that preparatory muscle activation is more vital than reactive muscle firing [16]. It is critical to pre-activate the lower limb musculature to maintain the dynamic knee stabilization [16]. Preparatory muscle activation in muscles crossing the joint decreases adverse knee joint angulations during rapid movements and impulsive joint loading [17]. It can also support the reduction of the strain on passive joint tissues such as the ACL [18].

A limited number of studies have reported on the risk factors for measures of preventing secondary ACL injury after ACL reconstruction. Although Knee valgus angle has been related to secondary ACL injury risk [7, 10], to the best of our knowledge, the relationship between preparatory knee muscle activation and knee valgus angle in ACLR subjects during the single-leg drop-landing task has not been examined. It is vital to understand the movement and forces across the ACLR limb during high-demand tasks, especially single limb landings to identify the biomechanical alterations that occur following ACL injury and reconstruction surgery [9]. Therefore, the aim of the current study was to investigate the relationship between preparatory knee muscle activity and the subsequent knee valgus angle at initial contact during single leg cross drop (SCD) landing following ACL reconstruction.

Methods

Participants

Twenty eight young athletes (18 to 30 years old) who recently sustained an ACL injury and underwent surgical reconstruction were recruited to partake in the study. Inclusion criteria consisted of the following: (1) completion of their rehabilitation program after ACLR, (2) clearance to return to the previous level of activity (high-level sports) by both their surgeon and physical therapist. The participant was expected to return to a pivoting or cutting (level 1 or 2) sport [19] (Table 1). Participants were excluded if they (1) suffered additional knee ligamentous injury on the involved limb during primary ACL injury (excluding grade 1 medial collateral ligament sprain), (2) reported lower extremity injury or surgery over the year before data collection, and (3) had a history of bilateral ACL injury or injury to the medial collateral ligament, posterior cruciate ligament, lateral collateral ligament, or meniscus in the contralateral and/or ipsilateral knee. Written informed consent was obtained from all participants before testing. The study has been approved at research ethics committee in the Faculty of Physical Education and Sports Sciences, University of Tehran.

Test Procedures

For each subject, the movements of the lower extremity segments were tracked with a three-dimensional motion capture system during a single-leg cross drop landing (SCD) [20]. EMG data were collected using 16-channel surface electromyography (EMG) system (ME6000-T16, Megawin, Mega Electronics Ltd, Kuopio, Finland) at 2000 Hz.

Table 1: Activity level classification [19]

Level	Sports Activity	Occupation Activity
I	Jumping, cutting, pivoting (soccer, team handball, basketball)	Activity comparable to Level I sports
II	Lateral movements, less pivoting than Level I (racket sports, martial arts, wrestling, gymnastics, aerobics)	Heavy manual labor, working on uneven surfaces
III	Straight ahead activities, no jumping or pivoting (running, mountaineering, weightlifting)	Light manual work
IV	Sedentary	Activities of daily living

The electrodes (Skintact, Leonhard Lang GmbH, Innsbruck, Austria) were secured over the muscle bellies of the vastus medialis (VM), vastus lateralis (VL), medial hamstring (MH) and lateral hamstring (LH) [21] according to the technique described by SENIAM (Surface Electromyography for the Non-invasive Assessments of Muscles). For EMG preparation, the skin was shaved and cleaned with isopropyl alcohol before the surface electrodes were applied. Electrode sites for the VM were located at 80% on the line between the anterior superior iliac spine and the superior aspect of the patella. For the VL, the position of the electrodes was at 2/3 on the line from the anterior superior iliac spine to the lateral side of the patella. The MH electrodes were placed at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia. The electrodes of LH were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. Two five-second maximum voluntary isometric contractions (MVICs) with 1 min rest between repetitions were accomplished for the purposes of normalization. Hamstring MVICs were performed while subjects were in prone position with the knee in 30º of flexion. Quadriceps MVICs were performed while subjects were seated with the knee in 90º of flexion.

Three-dimensional trajectory data were acquired using a 6-camera motion-analysis system (Motion Analysis Corporation, Santa Rosa, CA) and connected Cortex software (Version 2.6.8; Motion Analysis Corporation) at a sampling rate of 200 Hz. Twenty eight reflective markers were used to collect kinematic data. Twenty eight reflective markers were placed on anatomical landmarks according to Helen Hays methods to collect kinematic data. The markers were fixed on the landmarks using double-sided tape [22] (Figure 1). Static calibration trial was performed with the participant standing in a neutral position. All subjects performed a 5 min warm-up before testing. After collection of the MVICs and marker placement, subjects were instructed on how to execute the dynamic landing task and were permitted sufficient practice (3-5 repetition) trials for familiarization. For the SCD, the participant was positioned on top of a 30-cm box adjacent to an AMTI force platform (40×60 cm, OR-6-6-0™, Advanced Medical Technologies Inc., Watertown, MA, USA) and performed 3 trials of landing. The SCD is a unique task by which the roles of both the trunk and lower extremities in ACL injury may be measured [20]. The SCD was executed by balancing on an un-injured limb and then hopping forward and medially off the box. While in the air, the subject crosses the un-injured foot and land on the injured limb. All testing was done in the biomechanics laboratory of Sports Science Research Institute of Iran.

Data Analysis

The Cortex software from Motion Analysis was used to simultaneously record the EMG and motion data. By using customized software in MATLAB (Math Works, Natick, MA, USA) all EMG data were processed. DC offsets were removed, and electromyography data were band-pass filtered between 30 and 500 Hz with a zero-lag, fourth order Butterworth digital filter. The signal was then full-wave rectified and linearly enveloped using a low pass with a zero-lag, fourth order Butterworth filter at 6 Hz [23]. The average amplitude of two MVICs was used to normalize the dynamic contractions collected during each trial. Dynamic EMG data, recorded during the SCD landing task, were normalized to the peak muscle activity recorded during the MVIC. Muscle activity was described from 100 ms prior to ground contact to initial ground contact. Preparatory muscle activity was extracted as the mean values in a 100 ms window prior to initial ground contact [17]. It was calculated for all three trials and averaged for statistical analysis.

Figure 1: Retroreflective marker placement used to define the kinematic model.

Raw kinematic data of the knee was post-processed, reconstructed and labeled using Cortex software. The knee joint center was defined as the midpoint between the medial and lateral femoral epicondyles. Marker trajectories data were low-pass filtered using a 4th order zero-lag Butterworth filter at 12 Hz [24]. The data convention for knee valgus/varus angle was denoted as positive and negative, respectively. Vertical ground reaction force was recorded in order to calculate initial contact. Knee valgus at initial contact was extracted when vertical ground reaction forced exceeded 10N and EMG data 100 ms before initial contact.

Statistical Analysis

Descriptive data (means±SD) were calculated for the age, height, mass and time since injury/surgery for each subject group. Shapiro-Wilk analyses were used to test the normality of all EMG and knee kinematic data. In addition, the relationships between each EMG variables and knee valgus angle were assessed using Pearson correlation analyses. Statistical tests were performed with SPSS Statistics Version 25.0 (IBM Corporation, Armonk, NY), with an alpha level set to $P \leq 0.05$.

Results

Table 2 includes demographic information of all participants. Descriptive data (mean and standard deviation) of the preparatory VM, VL, MH and LH muscles activation of the involved limbs are presented in Table 3.

Table 2: Demographic information of subjects

Variable	Mean±SD
Age(Year)	23.83±5.49
Height (cm)	175.25±4.78
Mass (kg)	76.45±5.93
Months since surgery	23.75±6.30
Graft type	PT=10; STG=13; Allograft=5

*PT: patellar tendon; STG: semitendinosus/gracilis

Table 3: EMG preparatory muscle activity and knee valgus angle (means and standard deviations)

Variable	Mean	Std. Deviation
Knee Valgus Angle at Initial Contact (deg)	2.54	1.83
Vastus Medialis	0.27	0.22
Vastus Lateralis	0.70	0.60
Medial Hamstring	0.12	0.07
Lateral Hamstring	0.15	0.09

The preparatory activity of the medial hamstring and lateral hamstring muscles had a significant negative correlation with initial contact knee valgus angle ($P < 0.05$). There were no significant relationships between preparatory vastus medialis and vastus lateralis muscles activation and initial contact knee valgus angle ($P > 0.05$) (Table 4).

Discussion

The current study examined the relationship between the preparatory activity of hamstring and quadriceps muscles during SCD landing and the subsequent initial contact knee valgus angle to elucidate the potential associations between these factors and the second ACL injury risk following ACL reconstruction. Our findings support the hypothesis that there is a relationship between the amount of preparatory muscle activity prior to a landing and the subsequent initial contact knee valgus angle in ACLR subjects returning to sports activities after reconstruction. Investigating the movement characteristics of high-demand single-limb landing tasks through biomechanical analysis can provide valuable evidence about the risk of second ACL injury in those with ACLR who returned to sport. Single-limb landings characterize a rapid deceleration and have been noted to be a mechanism for ACL injury. Decreasing knee valgus during landing may be essential in reducing primary and second ACL injury incidence [7, 10].

According to our results, there were no significant relationships between preparatory quadriceps muscles activation and IC knee valgus angles during the SCD. The quadriceps and hamstring muscles maybe the most potent knee stabilizer with moment arms that resist knee valgus laxity, and support frontal plane motion and loads [25]. A possible explanation for our findings might be the fact that following ACL injury and reconstruction, knee extensor muscle group would be inhibited [26]. That is to say, quadriceps inhibition is a common and persistent problem after ACL injury and reconstruction [26]. Insufficiencies in neuromuscular control and dynamic strength, as well as the inhibition of muscular exertion may initiate a condition where the muscles cannot absorb the forced loading that prepare the joint for ground contact [12]. This may lead to compensatory movement patterns in reconstructed limb joints that result in changed kinematics and kinetics [12]. Quadriceps dysfunction post-ACLR might reduce the body's ability to endure landing forces in the frontal plane [27]. This hypothesis of altered quadriceps function on the frontal plane motion has been previously reported by Palmieri-Smith et al. (2008). In that study, they observed the relationship between decreased preparatory activation of the quadriceps and increased peak knee valgus angle in healthy women during landing [17]. They examined the relationship between the peak knee valgus angle and preparatory muscle activity. Twenty-one healthy adults were asked to perform five trials of a forward hop. They found out that a lower knee valgus angle was associated with increased preparatory vastus medialis activity [17]. This is a conceivable mechanism whereby quadriceps dysfunction in the injured limb may directly cause increased knee valgus and hip adduction during landing [28].

Our results also revealed that the preparatory activation of hamstring muscles (MH and LH) strategies employed by the ACLR subjects in this study had a significant association with their knee valgus angles at initial contact. The present results may be consistent with other reports following ACL–reconstruction, indicating that the movement patterns are altered during functional tasks [9, 13, 29]. The closed kinetic chain nature of landing requires the synchronous function of all lower extremity joints to diminish landing forces [30]. Lower extremity eccentric muscle function is known to be compromised after ACL injury and reconstruction, thereby impairing its ability to effectively attenuate impact loads, increase knee injury or re-injury risk [26, 28]. The protective mechanism, which is expressed as "compensatory hip and ankle joints movement patterns" is frequently detected during dynamic exercises and tasks to prevent overloading of the reconstructed knee joint [7, 13, 29]. Previous studies displayed that quadriceps muscle is inhibited following ACL injury and reconstruction. When this occurs, hip extensor (including the hamstring muscle group) activation might be upregulated to compensate for impaired quadriceps function [26, 31]. Coventry et

Table 4: Correlation between preparatory muscle activity and knee valgus angle at initial contact

		VM	VL	MH	LH
Knee Valgus Angle (IC)	Pearson Correlation	-0.28	0.25	-0.64^{**}	-0.72^{**}
	P value	0.143	0.186	0.001	0.001

al. (2006) reported that after healthy subjects performed a single-leg drop jump landing fatigue protocol, hip extensor exertion increased to compensate for reduced knee extensor and ankle plantar flexor impact force reduction capability [32]. The frontal and transverse plane imbalances may occur in the incidence of upregulated hip neuromuscular activation and vastus medialis inhibition [26, 31]. Conceivably, this changes the force transferred to the lower limb joints and results in abnormal alignment that causes asymmetry between the reconstructed and contralateral limbs [12]. Nyland et al. (2010) [29] found increased gluteus maximus EMG amplitudes and decreased vastus medialis EMG amplitudes at both men and women involved lower extremity [29]. They concluded that following ACL injury and surgery, patients show a larger tendency to utilize a hip strategy [29]. This enables the gluteus maximus and hamstring muscles to replace for quadriceps function across the knee for compound lower extremity extension during closed kinetic chain exercises and movements [29]. Our results show that individuals with a reconstructed ACL can resume their functional activities by employing compensatory lower extremity neuromuscular adaptations. The preparatory activation strategies employed by the subjects in this study contributed to their peak knee valgus angles. The preparatory activity of the knee muscles is linked to knee valgus angle at initial contact, and it may indicate a potential target of second ACL injury prevention programs.

This study like others is not without limitations. Subjects were with different graft type, patellar-tendon (n=10), semitendinosus/gracilis (n=13) and allograft (n=5). These findings hence may not be generalizable to all ACL reconstruction populations, where different surgical and rehabilitation approaches are applied. It is important to mention that because of the cross-sectional nature of the investigation without a control group, our results do not imply causation and we are unable to state if the observed results indicate the consequence of the injury and reconstruction. A longitudinal, prospective study design with repeated measures would have better described compensatory neuromuscular and biomechanical adaptations at the involved lower extremity. At the end, in our study, participants consist of male athletes which may limit the generalizability of the results to female athletes following ACLR.

Conclusion

The findings of this investigation support an association between the preparatory activity of knee muscles and frontal plane knee motion at initial contact. These data suggest that improvement in knee neuromuscular control during single-leg landing may reduce the likelihood of second ACL injury via a valgus loading mechanism following ACLR.

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Conflict of interest: None declared.

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