Factors affecting knee abduction during weight-bearing activities in individuals with anterior cruciate ligament reconstruction

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Abstract

Objective

To investigate if muscle strength and muscle activation patterns are associated with increased knee abduction during two functional tasks, commonly used in rehabilitation for individuals with anterior cruciate ligament reconstruction (ACLR).

Design

Cross-sectional study

Setting

Laboratory

Participants

24 women and 29 men approximately 7 months after ACLR.

Main Outcome Measures

Isometric peak torque of the trunk and lower extremity muscles were determined during maximal voluntary contractions. Trunk and lower extremity average muscle activation amplitude and peak knee abduction were evaluated during the single-leg squat (SLS) and the single-leg hop for distance (SLHD) for the injured side. Separate backward regressions were performed for men and women.

Results

In women, lower knee flexion and extension strength were associated with greater peak knee abduction during the SLS (B= 4.63 – 18.26, $p \leq 0.036$); lower knee flexion strength and iliocostalis activation on the non-injured side were associated with greater peak knee abduction during the SLHD (B= 0.60 – 20.48, $p \leq 0.043$). No associations between muscle function and peak knee abduction were found in men.

Conclusions

Muscle function may contribute differently to knee abduction in men and women after ACLR. This should be considered when designing rehabilitation programs to reduce knee abduction in these patients.

Key words: anterior cruciate ligament injury, knee abduction, strength, muscle activation

Background

Peak knee abduction during weight-bearing activities is suggested to be greater in patients after anterior cruciate ligament deficiency (ACLD) and reconstruction (ACLR) than before injury [1]. Greater 3D peak knee abduction is also reported to be associated with a higher risk of sustaining an anterior cruciate ligament (ACL) injury [2]. Thus, a large degree of knee abduction during weight-bearing activities is considered to be an undesirable movement pattern. According to a recent systematic review, numerous studies on modifiable factors contributing to this supposedly undesirable movement pattern have been conducted in healthy individuals, but are poorly investigated in patients with ACL injury [3].

In healthy individuals, previous studies report no or weak associations between lower extremity strength and knee abduction, but a moderate association between lower trunk strength and reduced gluteus maximus (Gmax) activation amplitude and greater knee abduction during functional tasks including the single-leg squat (SLS) and the single-leg hop for distance (SLHD), two tasks commonly used to evaluate rehabilitation in individuals with ACLR [3]. However, alterations in sensorimotor function are reported after ACL injury. Specifically, patients with ACL injury appear to have reduced hip and knee muscle strength [4], decreased voluntary quadriceps activation amplitude [5], delayed activation onset of lower extremity muscles [6, 7], and an increased average activation amplitude of the posterior thigh and calf muscles [8, 9] during functional tasks compared to non-injured individuals. Since the hamstring muscles act as ACL agonists and thereby resist anterior tibial translation[10], it has been suggested that the increase in hamstring and gastrocnemius activity are compensatory mechanisms intended to maintain neuromuscular control after the loss of the ACL [10]. Thus, the different movement patterns observed in patients with

ACLD/ACLR may be related to changes in sensorimotor function after injury. Consequently, the factors contributing to knee abduction in this group of patients may be different from those observed in healthy individuals.

Given the reported role of knee abduction during weight bearing activities upon functional performance and subsequent injury risk, identifying the modifiable factors that influence knee abduction would help in the design of targeted ACLR rehabilitation programs. Also, knowledge of any possible gender differences in the sensorimotor factors that affect knee abduction will enable a more patient-tailored approach towards rehabilitation aimed at decreasing knee abduction. The aim of this study was to investigate the association between muscle function (muscle strength and muscle activation amplitude) and peak knee abduction during the SLS and the SLHD.

Methods

This study adheres to the STROBE guidelines for cross-sectional studies [11].

Participants

An invitation to participate in this study was sent out to all patients that had undergone ACLR at the Department of Orthopedics, Skåne University Hospital, Sweden, between June 1st, 2015 and March 15th, 2016 (n=165). In addition, the study was advertised at physical therapy clinics in the region of Skåne, Sweden. Inclusion criteria were: 1) individuals with ACLR (any graft) with or without associated injuries to other structures of the knee, 2) between 16 and 40 weeks after reconstructive surgery, 3) 18 to 39 years of age, 4) progressed to jumping exercises as part of their rehabilitation. Exclusion criteria were: 1) use of external devices to assist with weight-bearing (e.g. crutches and/or braces), 2) no longer participating in supervised rehabilitation, 3) medial collateral ligament surgery, 4) other injuries or diseases overriding the symptoms of the knee injury. In total, 68 individuals consented to participate (61 from the Department of Orthopedics and 7 from physical therapy clinics). Finally, 24 women and 29 men with ACLR were included (Figure 1).

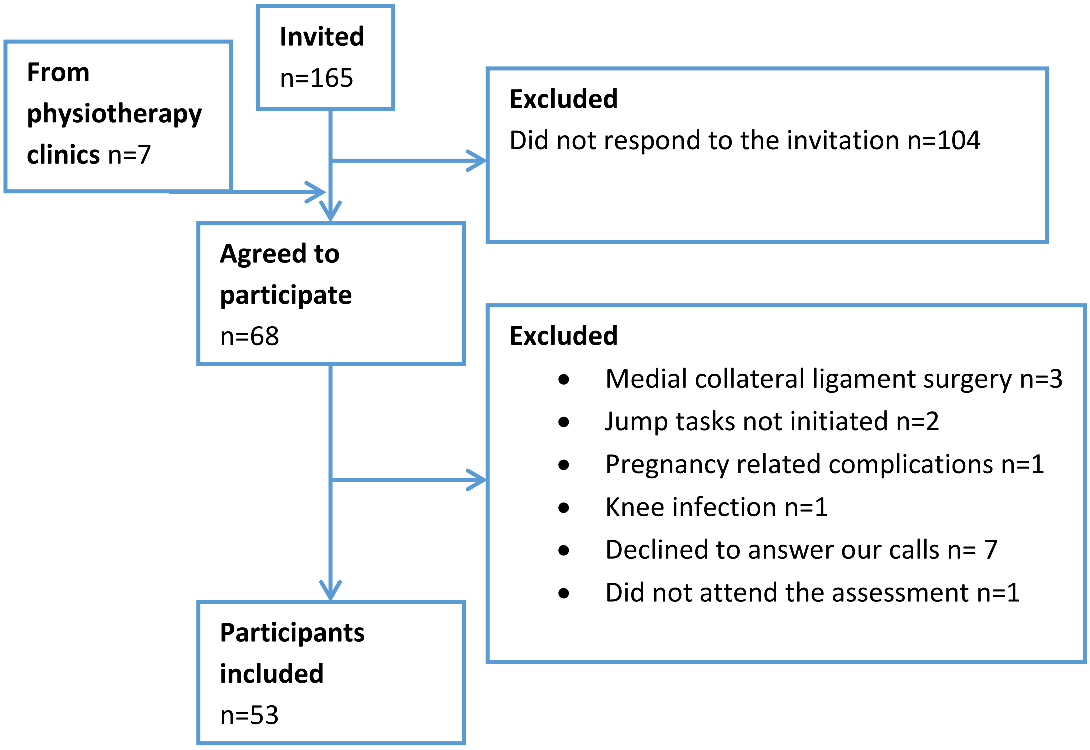

Figure 1. Flowchart of the inclusion process.

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Procedures

Participant body mass was obtained with a digital weighing scale, and other participant characteristics, including Tegner activity score [12] and surgical characteristics were obtained via self-report. Assessments were performed on the ACLR leg (both sides for iliocostalis activation amplitude) and were conducted in the order described below. Participants wore shorts, sports bra (women) and their own personal athletic footwear. Test-retest reliability of muscle strength and activation amplitude, and knee kinematics were evaluated in 9 healthy adults, tested one week apart.

Muscle strength

Isometric peak torque of hip external rotation, hip abduction, hip extension, knee flexion, knee extension, and side bridge peak force, were assessed with a hand-held dynamometer (Commander Echo, JTECH Medical, Salt Lake City, Utah, USA). The lever arm for each of the torque measurements was calculated as the distance between the dynamometer location and the rotation axis of the joint, except for the side-bridge test which was nominally defined as the distance between acromion and the lateral malleolus. To keep the dynamometer in position, a fixation belt was strapped around the assessor or the bench during all assessments and the participant was encouraged to push the leg/trunk against the dynamometer as forcefully as they could. For hip external rotation, hip extension and knee flexion strength, the participant was lying in a prone position with one belt stabilizing the contralateral thigh and one belt stabilizing the pelvis. The participant held the leg in 90 degrees of knee flexion and the dynamometer was placed 5 cm proximal to the medial malleolus for hip external rotation [13], at the distal thigh for hip extension [14] and on the shank just proximal to the malleoli for knee flexion strength [15]. For hip abduction strength, the participant was lying in a supine position with two belts stabilizing the contralateral thigh and pelvis, respectively. The dynamometer was placed on the lateral side just proximal to the knee joint, and the participant was then told to abduct the injured leg without rotating the hip [16]. Knee extension strength was assessed in a seated position with the knee flexed to 90 degrees with a belt stabilizing both thighs. The participant held on to the bench for stability. The dynamometer was placed just proximal to the talocrural joint [15]. For side-bridge trunk strength, the participant was lying on their injured side, placing support on the elbow and the foot of the injured leg [17]. The dynamometer was placed at the iliac crest. All strength tests were repeated three times. Each contraction was maintained for 5 seconds with at least 15 seconds of rest in between. For each test, the peak value of three trials was calculated in Newton meters (Nm) by multiplying the peak force value with the corresponding lever arm. These values were then normalized to body mass (Nm/kg). Test-retest reliability was good to excellent for the included strength variables ($ICC_{3,1}$=0.62-0.95, Online resource 1, Table 1).

Kinematics and electromyography

Three-dimensional (3D) kinematics were collected at 150 Hz during the performance of the SLS and SLHD using an 8-camera optoelectronic motion analysis system (Qualisys, version 2.12, Gothenburg, Sweden). A combination of individual reflective markers and marker clusters were attached to the trunk, pelvis and injured leg (thigh, shank and foot) of participants to define joint axes and track segmental kinematics.

Muscle activation patterns were synchronously collected with the kinematic data, using surface electromyography (EMG; Desktop DTS, Noraxon U.S.A. Inc, Scottdale, Arizona, USA), with a sampling frequency of 1500 Hz and a low pass filter of 500 Hz. Disposable self-adhesive dual EMG electrodes (Noraxon, USA. Inc, Scottdale, Arizona, USA) with an inter-electrode distance of 17.5 mm were attached to Gmax, gluteus medius (Gmed), semitendinosus (ST), vastus medialis (VM) medial gastrocnemius (MG) and Iliocostalis (IC). Prior to the placement of electrodes, the skin was shaved and lightly abraded with a medical abrasion gel (Nuprep, Weaver and company, Aurora, Colorado, USA). All electrodes were placed parallel to the muscle fibers and at locations according to the SENIAM guidelines [18]. Maximum voluntary contraction (MVC) data for each muscle was calculated as the maximum value obtained during muscle strength tests, i.e., hip extension for Gmax activation, hip abduction for Gmed activation, knee flexion for ST activation, knee extension for VM activation, plantar flexion for MG activation and trunk extension for IC activation.

Data processing

Marker trajectories were reconstructed and labeled in Qualisys Track Manager (version 2.12). All further processing was carried out in Visual 3D (version 5.02, C-Motion, Germantown, MD, USA). Marker trajectories were filtered with a 12 Hz, 4th order, low pass Butterworth filter [19]. 3D knee kinematics throughout the movement trials were calculated using a joint coordinate system approach [20]. For the SLS, the flexion phase was defined as the time from when the knee flexion angle increased by more than 2 degrees from full extension at the commencement of the squat to when the knee flexion angle reached 2 degrees less than the angle achieved at full flexion (the bottom of the squat). An adaptation of the methods of Fellin et al., [21] was used to define foot contact in the SLHD as the time at which lowest height of the distal heel or toe marker occurred (whichever occurred first). The flexion phase for the SLHD was defined as the time frame from foot contact to when the knee flexion angle reached 2 degrees less than the peak knee flexion angle achieved during the landing. Peak knee abduction was defined as the maximum knee abduction angle that occurred during the flexion phase of each trial (Figure 2a-d); the mean values from the five SLSs and three SLHDs were included in the analyses. There was good to excellent test-retest reliability for peak knee abduction during the SLS ($ICC_{3,5}$=0.894) and SLHD ($ICC_{3,3}$=0.773); Online resource 1, Table 2).

The raw EMG data were ECG-reduced, high-pass filtered at 20 Hz, full-wave rectified and smoothed by a root mean square algorithm over 50 ms windows (MyoRESEARCH Biomechanical Analysis, Noraxon, version 3.6). All processed EMG signals for each muscle were then normalized to the maximum value from the respective MVC trials. The mean values obtained during the flexion phase of the five SLSs and three SLHDs were included in the analyses. The test-retest reliability for the muscle function variables was poor to excellent ($ICC_{3,k}$=0 – 0.916) (Online resource 1, Table 2). All variables with poor reliability (ICC<0.4 [22]) were excluded from further analysis, i.e., VM and GC activation amplitude for the SLS and activation amplitude for all muscles except IC both sides for the SLHD.

Functional tasks

The single-leg squat (SLS) was performed as described elsewhere [23], with modification to include 60° of knee flexion, without finger-tip support and arms by the side of the body. The participant stood on the injured leg with the contralateral leg lifted from the floor. The participant was then instructed to flex the knee until he/she was touching a bench with their buttocks, without putting any weight on the bench, and then return to extension. The bench was placed behind the participant and was adjusted in height to ensure that the deepest part of the squat was set to ~60° of knee flexion. One practice trial was provided. The squat was repeated five times at a speed of 3 seconds per complete squat (upright standing to upright standing).

Each participant then performed a modified version of the single-leg hop for distance (SLHD), with arms free to enable a more functional execution of the task [24]. The participant stood on the injured leg with the toes behind a marked line, and with the contralateral leg lifted from the floor by flexing at the hip and knee. The subject was then instructed to jump forwards as far as possible (arm swing allowed), taking off and landing on the same foot, and to maintain balance on landing for 3-5 seconds. Two practice trials were provided, followed by three test trials. If there was more than 30 cm between the longest and shortest jump, additional jumps were performed until the increase in jump distance was less than 30 cm.

Statistics

All statistics were calculated using SPSS version 24 (IBM Corporation, New York, USA). Pearson's correlation coefficient (continuous data: age, BMI, time since ACLR), Spearman's rank correlation (ordinal data: activity level), and independent T-tests (binary variables: injury data) were used to investigate associations between participant characteristics and peak knee abduction to identify possible covariates for the regression analyses. Since uninjured females seem to have both reduced hip strength [25], different muscle activity patterns [10] and greater knee abduction angles during activity [26] when compared with their male counterparts, separate analyses were performed for men and women.

Independent T-tests and Cohen's d (mean difference/$SD_{pooled)}$ were used to assess possible gender differences in peak knee abduction during each task.

Pearson's correlation coefficient was used to explore the associations between each muscle function variable (strength and activation amplitude) and peak knee abduction angle, in separate analysis for the SLS and SLHD. For all correlations, Cohen's thresholds were applied: ≥0.1=small, ≥0.3=moderate, ≥0.5=large and ≥0.7=very large correlation [27]. Next, backward linear regression models, adjusting for potential covariates, were applied. All muscle function variables that were at least moderately correlated with peak knee abduction (r ≥0.3) were added in to the models with the specific muscle function variables as independent factors and peak knee abduction as the dependent factor. The original data and residuals were checked for normality by visual inspection of histogram, Q-Q plots and the Kolmogorov-Smirnov test (p>0.05=normal distribution). All variables met the assumptions of normality. In addition, a variance inflation factor (VIF) of <4 was used to ensure that no collinearity between the included independent factors were present. A p-value less than or equal to 0.05 was considered statistically significant. Since this study had an exploratory design, no adjustments for multiple comparisons were made [28].

Results

Forty-six percent (n=24) of the participants were women (mean age 26 ± 7 years, mean BMI 24.3 ± 3.3) and fifty-four percent (n=29) were men (mean age 27 ± 6.7 years, mean BMI 25.1 ± 3.2) (Table 1). Due to noise in raw EMG signals, some EMG channels had to be excluded leaving 72 – 100% data for each muscle in the analyses. Descriptive data for the different muscle function variables are presented in online resource 1, Table 3. The mean hop distance was 84 ± 29.4 cm for women and 113 ± 35.2 cm for men. Women performed both the SLS (mean difference = -3.96°, 95% CI; -6.48 – -1.45, p=0.003, Cohen's d=0.91) and the SLHD (mean difference = -3.59°, 95% CI; -6.50 – -0.57, p=0.017, Cohen's d=0.68) with greater peak knee abduction compared to men. A higher BMI was associated with greater peak knee abduction during the SLS and the SLHD in both genders ($r \geq -0.551$, $p<0.005$) and was, thus, included as a covariate in the regression analyses. No associations were observed between any other demographic variables, hop distance or peak knee flexion and peak knee abduction during the respective tasks ($p \geq 0.367$).

Table 1. Characteristics of the participants

	Women (n=24)	**Men** (n=29)
Age *mean (SD)*	26 (7.0)	27 (6.2)
BMI *mean (SD)*	24.29 (3.25)	25.06 (3.22)
TAS pre injury *median (quartiles)*	8 (6-9)	8 (6-9)
TAS at test occasion *median (quartiles)*	3 (3-4)	3 (2-4.5)
Time since rec *weeks mean (SD)*	27.42(6.90)	28.93 (6.56)
Injured knee right *n (%)*	10 (42)	10 (34.5)
Graft type		
Hamstring n (%)	22 (92)	27 (93)
Patella tendon n (%)	1 (4)	2 (7)
Donated n (%)	1 (4)	-
Re-surgery *n (%)*	5 (21)	2 (7)
Contralateral ACL injury *n (%)*	3 (13)	2 (7)
Associated injuries *n (%)*	17 (71)	22 (76)
Medial meniscus injury n (%)	13 (54)	12 (41)
Lateral meniscus injury n (%)	7 (29)	12 (41)
Cartilage damage n (%)	3 (13)	8 (28)
Collateral ligament injury n (%)	6 (25)	7 (24)

SD=standard deviation, TAS=Tegner activity scale

In women, hip abduction, hip extension, hip external rotation, knee extension and knee flexion peak torque as well as Gmed and ST activation amplitude were entered into the regression model of the SLS, as they were at least moderately correlated with peak knee abduction (r ≥0.3; Online resource 1, Table 4). For the SLHD, the corresponding variables were hip abduction and knee flexion peak torque and IC activation amplitude on the contralateral side. Lower knee flexion (B=18.26, p=0.005) and lower knee extension (B=4.63, p=0.036) peak torque were associated with greater peak knee abduction during the SLS (R^2=0.471); lower knee flexion peak torque (B=20.48, p=0.001) and lower IC activation amplitude on the contralateral side (B=0.60, p=0.043) were associated with greater peak knee abduction during the SLHD (R^2=0.600) (Table 2).

In men, Gmed and IC activation amplitude on the injured side were entered into the regression model of the SLS. For the SLHD, hip external rotation and side bridge peak torque were entered in to the model (Online resource 1, Table 4). The regression analyses revealed no association between the different muscle function variables and peak knee abduction in either the SLS or SLHD (Table 2). The VIF ≤ 2.59 indicated no collinearity between the independent factors.

Discussion

In this exploratory study, lower knee flexion and extension peak torque were associated with greater peak knee abduction during the SLS in women, whereas lower knee flexion peak torque and lower IC activation amplitude on the contralateral side were associated with greater peak knee abduction during the SLHD. We found no significant associations between muscle peak torque or muscle activation amplitude and peak knee abduction during the two tasks in men. Women with ACLR performed both tasks with greater peak knee abduction than their male counterparts.

Lower knee extension strength was associated with greater peak knee abduction in women during the SLS, and lower knee flexion strength was associated with greater peak knee abduction in both tasks, indicating that both knee extension and knee flexion strength are important for controlling frontal plane knee motion during activity. Both knee flexors and knee extensors are suggested to be important for controlling knee stability during knee abduction loading [29]. Co-activation of the quadriceps and hamstring muscles seem to be particularly effective in preventing frontal plane knee movements when they are forced to produce flexion and extension moments [30], such as, during the performance of the SLS and the landing after a jump. Thus, given the suggested relationship between greater knee abduction during weight-bearing activities and an increased risk of sustaining a subsequent knee injury [31, 32], knee muscle strengthening may be an important factor to consider in rehabilitation and the prevention of subsequent knee injuries in women.

In line with the study by Nakagawa et al., [33] we found no relationship between IC activation amplitude on the injured side and peak knee abduction. However, to our knowledge, this is the first time IC activation amplitude on the contralateral side has been investigated. We found that lower IC activation amplitude on the contralateral side was associated with greater peak knee abduction in the injured leg during the SLHD in females. One possible explanation for this result may be that IC activation amplitude on the contralateral side may be related to trunk lean towards the injured side [34-36]. Increased trunk lean towards the injured side has been reported to be associated with greater peak knee abduction [33], an increased knee abduction moment [37, 38] and increased knee injury risk [39, 40]. Thus, proximal kinematic adjustments, including IC activation amplitude on the contralateral side may be associated with peak knee abduction during landing after a jump. Further studies are, however, needed to confirm our finding and to assess whether muscle activation amplitude on the contralateral side may be associated with lateral trunk lean towards the injured side.

We found no association between any of the muscle function variables and knee abduction during the two tasks in men. One explanation for this may be attributed to differences in the magnitude of peak knee abduction between men and women. In line with previous research in women with an intact ACL [26], and women with ACL deficiency [41], we found women to exhibit greater knee abduction compared to men in both functional tasks. This result indicates gender differences in frontal plane knee movements after ACLR, which may contribute to the risk of sustaining a second ACL injury in women [31, 32]. Our results indicate that adequate strength and activation of trunk and lower extremity muscles may be important for knee abduction in women, whereas other factors may affect knee abduction in men. Women have previously been suggested to exhibit different muscle activity patterns [10], as well as less relative trunk and lower extremity strength, compared to men [25, 42]. Taken together, these differences in muscle strength and muscle activation patterns between men and women may contribute to an increased ability to control frontal plane movements during activity in men.

A recent systematic review in healthy individuals reported lower side-bridge strength and reduced Gmax activation amplitude, but not lower extremity muscle strength to be associated with greater knee abduction during functional tasks [3]. In line with this review, we found no relationship between hip muscle strength and knee abduction after ACLR. In contrast, we did find a significant association between knee strength and knee abduction in women, whereas side-bridge strength and Gmax activation amplitude did not predict knee abduction in our study. Given the known alterations in sensorimotor function after ACL injury, such as reduced knee strength [4] and decreased quadriceps activation amplitude [5], this result implies that adequate knee muscle strength is important for controlling frontal plane knee motion after sustaining an ACL injury whereas other factors may be more important for knee abduction in healthy individuals.

Strengths and Limitations

To our knowledge, this is the first study investigating the combined effects of muscle strength and activation amplitude as possible underlying mechanisms of knee abduction in men and women with ACLR. A strength of this study is that we have included individuals currently undergoing rehabilitation, with different activity levels, participating in different sports, age 18 to 39 years old, in an effort to reflect a clinically relevant population with ACLR.

This study has some limitations. First, all participants performed the tasks with an amount of knee abduction that was within normal values for drop jump and cutting tasks [43], implying that they were well trained during their supervised rehabilitation to keep their knee in line with the hip and ankle. In fact, men performed the SLS with a very small amount of knee abduction (0.74±3.02 degrees) whereas during the SLHD, they landed with their knee in slight knee adduction. It is possible that our results would differ if participants had performed the tasks with more pronounced knee abduction. Second, we only included peak knee abduction as our outcome. Including other measures of knee abduction such as knee abduction at initial contact or knee abduction excursion may have led to a different result. However, in contrast to knee abduction excursion [44, 45], peak knee abduction during movements does not seem to be related to static alignment [46, 47]. Peak knee abduction may, thus, be a more representative measure of neuromuscular function than for example knee abduction excursion. Third, all except four of the participants were reconstructed using a hamstring graft. Hamstring harvesting is associated with knee flexor strength deficits, altered morphologic muscle characteristics and altered response of the hamstring muscle during rapid movements [48-50] which may have influenced the results for knee flexion strength and knee abduction. Thus, including more participants with a patella graft may have led to a different result. Fourth, two of the muscle activation variables during the SLS (VM and GC) and five of the muscle activation variables during the SLHD (Gmax, Gmed, ST, VM and GC) showed poor reliability in our test—retest cohort of 9 healthy individuals and were thus excluded from the analyses. Several factors, including, participants' positioning during the tasks and subsequent compensatory strategies to maintain balance, familiarity with the task, electrode placement, and reassessment of MVC, will have influenced our test-retest reliability. Consequently, we cannot rule out that some of these muscle activation variables may be associated with knee abduction. Whilst there is some evidence of good to excellent within-session reliability for trunk and lower extremity muscles in some tasks (i.e. running and single leg landings) [51, 52], prior to further investigation of the role of muscle activation patterns in knee abduction kinematics, it is recommended that test-retest reliability is established in a larger cohort of individuals with ACL deficiency and ACLR. Fifth, we only included patients with ACLR. Thus, further studies are needed to confirm if the result in this study is true also for patients with an ACL deficient knee. Finally, this is a cross-sectional study and, thus, no conclusions on causal relationship can be made.

Conclusion

After ACLR, knee muscle strength and trunk muscle activation amplitude may contribute to knee abduction in women whereas lower extremity function seems to be less important for knee abduction in men. Gender differences in the contribution of muscle function for knee abduction should be considered in ACLR rehabilitation programs aimed at reducing knee abduction in these patients.

References

1. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA: **Anterior cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: the JUMP-ACL study**. *British journal of sports medicine* 2015, **49**(3):188-195.
2. Hewett TE, Myer GD, Ford KR, Heidt RS, Jr., Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P: **Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study**. *The American journal of sports medicine* 2005, **33**(4):492-501.
3. Cronstrom A, Creaby MW, Nae J, Ageberg E: **Modifiable Factors Associated with Knee Abduction During Weight-Bearing Activities: A Systematic Review and Meta-Analysis**. *Sports medicine (Auckland, NZ)* 2016.
4. Petersen W, Taheri P, Forkel P, Zantop T: **Return to play following ACL reconstruction: a systematic review about strength deficits**. *Archives of orthopaedic and traumatic surgery Archiv fur orthopadische und Unfall-Chirurgie* 2014, **134**(10):1417-1428.
5. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD: **Quadriceps activation following knee injuries: a systematic review**. *Journal of athletic training* 2010, **45**(1):87-97.
6. Dingenen B, Janssens L, Luyckx T, Claes S, Bellemans J, Staes FF: **Lower extremity muscle activation onset times during the transition from double-leg stance to single-leg stance in anterior cruciate ligament injured subjects**. *Hum Mov Sci* 2015, **44**:234-245.
7. Steele JR, Brown JM: **Effects of chronic anterior cruciate ligament deficiency on muscle activation patterns during an abrupt deceleration task**. *Clin Biomech (Bristol, Avon)* 1999, **14**(4):247-257.
8. Shanbehzadeh S, Mohseni Bandpei MA, Ehsani F: **Knee muscle activity during gait in patients with anterior cruciate ligament injury: a systematic review of electromyographic studies**. *Knee Surg Sports Traumatol Arthrosc* 2015.

9. Perraton L, Clark R, Crossley K, Pua YH, Whitehead T, Morris H, Telianidis S, Bryant A: **Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function**. *Knee Surg Sports Traumatol Arthrosc* 2016.
10. Cowling EJ, Steele JR: **Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates**. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 2001, **11**(4):263-268.
11. von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP: **The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: guidelines for reporting observational studies**. *International journal of surgery (London, England)* 2014, **12**(12):1495-1499.
12. Tegner Y, Lysholm J: **Rating systems in the evaluation of knee ligament injuries**. *Clin Orthop Relat Res* 1985(198):43-49.
13. Kemp JL, Schache AG, Makdissi M, Sims KJ, Crossley KM: **Greater understanding of normal hip physical function may guide clinicians in providing targeted rehabilitation programmes**. *Journal of science and medicine in sport / Sports Medicine Australia* 2013, **16**(4):292-296.
14. Bell DR, Padua DA, Clark MA: **Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement**. *Archives of physical medicine and rehabilitation* 2008, **89**(7):1323-1328.
15. Beutler A, de la Motte S, Marshall S, Padua D, Boden B: **MUSCLE STRENGTH AND QUALITATIVE JUMP-LANDING DIFFERENCES IN MALE AND FEMALE MILITARY CADETS: THE JUMP-ACL STUDY**. *Journal of sports science & medicine* 2009, **8**:663-671.
16. Pua YH, Wrigley TV, Cowan SM, Bennell KL: **Intrarater test-retest reliability of hip range of motion and hip muscle strength measurements in persons with hip osteoarthritis**. *Archives of physical medicine and rehabilitation* 2008, **89**(6):1146-1154.
17. McGill SM, Childs A, Liebenson C: **Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database**. *Archives of physical medicine and rehabilitation* 1999, **80**(8):941-944.
18. Hermens H, Freriks B, Disselhorst-Klug C, Rau G: **Development of recommendations for SEMG sensors and sensor placement procedures.** *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 2000, **10**(5):361–374.
19. Robertson DG, Dowling JJ: **Design and responses of Butterworth and critically damped digital filters**. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 2003, **13**(6):569-573.
20. Grood ES, Suntay WJ: **A joint coordinate system for the clinical description of three-dimensional motions: application to the knee**. *Journal of biomechanical engineering* 1983, **105**(2):136-144.
21. Fellin RE, Rose WC, Royer TD, Davis IS: **Comparison of methods for kinematic identification of footstrike and toe-off during overground and treadmill running**. *Journal of science and medicine in sport / Sports Medicine Australia* 2010, **13**(6):646-650.
22. Landis JR, Koch GG: **The measurement of observer agreement for categorical data**. *Biometrics* 1977, **33**(1):159-174.
23. Ageberg E, Bennell KL, Hunt MA, Simic M, Roos EM, Creaby MW: **Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat**. *BMC musculoskeletal disorders* 2010, **11**:265.
24. Zätterström R, Fridén T, Lindstrand A, Moritz U: **Rehabilitation following acute anterior cruciate ligament injuries--a 12-month follow-up of a randomized clinical trial**. *Scandinavian journal of medicine & science in sports* 2000, **10**(3):156-163.
25. Thorborg K, Bandholm T, Holmich P: **Men are stronger than women-also in the hip**. *Journal of science and medicine in sport / Sports Medicine Australia* 2013, **16**(5):E1-3.

26. Cronstrom A, Creaby MW, Nae J, Ageberg E: **Gender differences in knee abduction during weight-bearing activities: A systematic review and meta-analysis**. *Gait & posture* 2016, **49**:315-328.
27. Cohen J: **Statistical Power Analysis for the Behavioral**

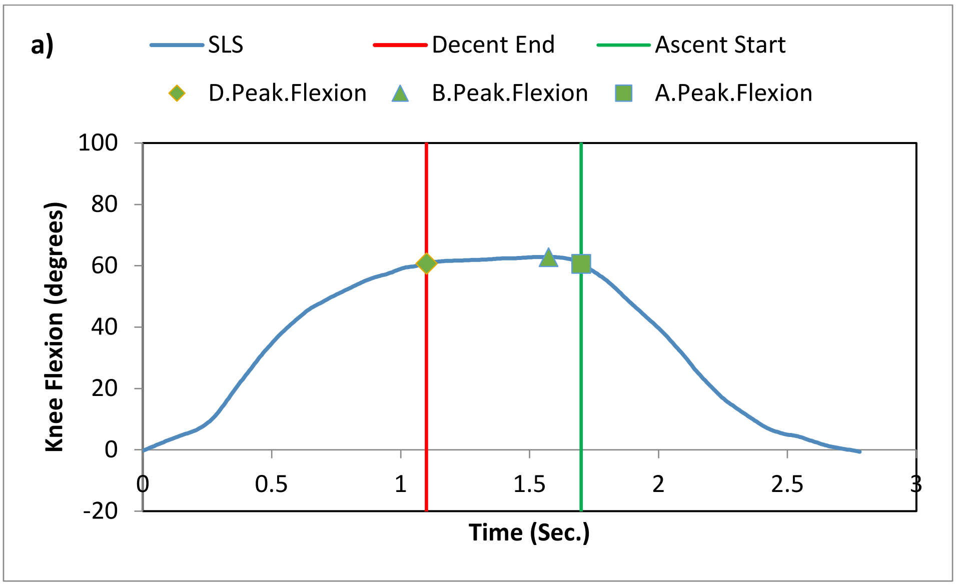
Sciences, 2 edn. Hillsdales, NJ: Lawrence Erlbaum; 1988.
28. Bender R, Lange S: **Adjusting for multiple testing--when and how?** *Journal of clinical epidemiology* 2001, **54**(4):343-349.
29. Dhaher YY, Tsoumanis AD, Rymer WZ: **Reflex muscle contractions can be elicited by valgus positional perturbations of the human knee**. *J Biomech* 2003, **36**(2):199-209.
30. Lloyd DG, Buchanan TS, Besier TF: **Neuromuscular biomechanical modeling to understand knee ligament loading**. *Medicine and science in sports and exercise* 2005, **37**(11):1939-1947.
31. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, Hewett TE: **Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport**. *The American journal of sports medicine* 2010, **38**(10):1968-1978.
32. Krosshaug T, Steffen K, Kristianslund E, Nilstad A, Mok KM, Myklebust G, Andersen TE, Holme I, Engebretsen L, Bahr R: **The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes**. *The American journal of sports medicine* 2016.
33. Nakagawa TH, Maciel CD, Serrao FV: **Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain**. *Manual therapy* 2015, **20**(1):189-193.
34. Beith ID: **Reflex control of ipsilateral and contralateral paraspinal muscles**. *Exp Brain Res* 2012, **218**(3):433-440.
35. Zedka M, Kumar S, Narayan Y: **Electromyographic response of the trunk muscles to postural perturbation in sitting subjects**. *J Electromyogr Kinesiol* 1998, **8**(1):3-10.
36. Peach JP, Sutarno CG, McGill SM: **Three-dimensional kinematics and trunk muscle myoelectric activity in the young lumbar spine: a database**. *Arch Phys Med Rehabil* 1998, **79**(6):663-669.
37. Mundermann A, Asay JL, Mundermann L, Andriacchi TP: **Implications of increased medio-lateral trunk sway for ambulatory mechanics**. *Journal of biomechanics* 2008, **41**(1):165-170.
38. Weltin E, Mornieux G, Gollhofer A: **Influence of gender on trunk and lower limb biomechanics during lateral movements**. *Research in sports medicine (Print)* 2015, **23**(3):265-277.
39. Hewett TE, Torg JS, Boden BP: **Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism**. *British journal of sports medicine* 2009, **43**(6):417-422.
40. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J: **Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study**. *The American journal of sports medicine* 2007, **35**(7):1123-1130.
41. Yamazaki J, Muneta T, Ju YJ, Sekiya I: **Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls**. *Knee Surg Sports Traumatol Arthrosc* 2010, **18**(1):56-63.
42. Willson JD, Ireland ML, Davis I: **Core strength and lower extremity alignment during single leg squats**. *Med Sci Sports Exerc* 2006, **38**(5):945-952.
43. Fox AS, Bonacci J, McLean SG, Spittle M, Saunders N: **What is normal? Female lower limb kinematic profiles during athletic tasks used to examine anterior cruciate ligament injury risk: a systematic review**. *Sports medicine (Auckland, NZ)* 2014, **44**(6):815-832.
44. Nguyen AD, Shultz SJ, Schmitz RJ: **Landing Biomechanics in Participants With Different Static Lower Extremity Alignment Profiles**. *Journal of athletic training* 2015.

45. Nguyen AD, Shultz SJ, Schmitz RJ, Luecht RM, Perrin DH: **A preliminary multifactorial approach describing the relationships among lower extremity alignment, hip muscle activation, and lower extremity joint excursion**. *Journal of athletic training* 2011, **46**(3):246-256.
46. Harty CM, DuPont CE, Chmielewski TL, Mizner RL: **Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks**. *Scandinavian journal of medicine & science in sports* 2011, **21**(1):98-105.
47. Pantano KJ, White SC, Gilchrist LA, Leddy J: **Differences in peak knee valgus angles between individuals with high and low Q-angles during a single limb squat**. *Clinical biomechanics (Bristol, Avon)* 2005, **20**(9):966-972.
48. Ardern CL, Webster KE, Taylor NF, Feller JA: **Hamstring strength recovery after hamstring tendon harvest for anterior cruciate ligament reconstruction: a comparison between graft types**. *Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association* 2010, **26**(4):462-469.
49. Konrath JM, Vertullo CJ, Kennedy BA, Bush HS, Barrett RS, Lloyd DG: **Morphologic Characteristics and Strength of the Hamstring Muscles Remain Altered at 2 Years After Use of a Hamstring Tendon Graft in Anterior Cruciate Ligament Reconstruction**. *The American journal of sports medicine* 2016, **44**(10):2589-2598.
50. Ristanis S, Tsepis E, Giotis D, Stergiou N, Cerulli G, Georgoulis AD: **Electromechanical delay of the knee flexor muscles is impaired after harvesting hamstring tendons for anterior cruciate ligament reconstruction**. *The American journal of sports medicine* 2009, **37**(11):2179-2186.
51. Smoliga JM, Myers JB, Redfern MS, Lephart SM: **Reliability and precision of EMG in leg, torso, and arm muscles during running**. *J Electromyogr Kinesiol* 2010, **20**(1):e1-9.
52. Cavanaugh MT, Aboodarda SJ, Behm DG: **Intrasession and Intersession Reliability of Quadriceps' and Hamstrings' Electromyography During a Standardized Hurdle Jump Test With Single Leg Landing**. *Journal of strength and conditioning research / National Strength & Conditioning Association* 2017, **31**(6):1601-1609.

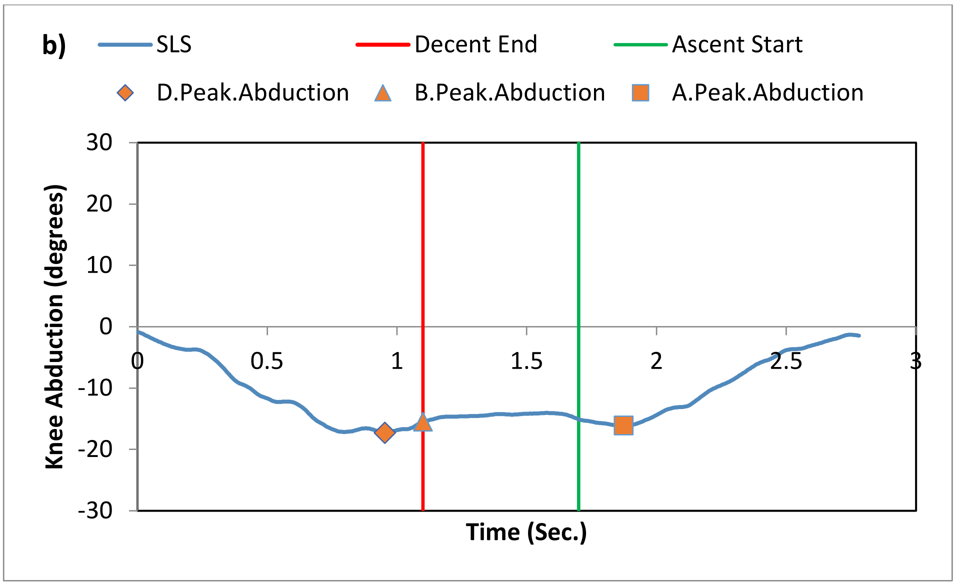
Table 2. Linear regression coefficients of the contribution of muscle function variables for knee abduction during the single-leg squat and single-leg hop for distance

	Peak Knee abduction (degrees)					
Women	**Single-leg squat** (n=24)					
	B	**SE B**	**95% CI**	**β**	**p-value**	**R^2** (adjusted R^2)
Knee flexion peak torque	18.26	5.82	6.12;30.41	0.540	0.005*	0.471 (0.391)
Knee extension peak torque	4.63	2.07	0.32;8.94	0.381	0.036*	
BMI	-0.35	0.28	-0.94;0.24	-0.210	0.231	
	Single-leg hop for distance (n=22)					
Knee flexion strength	20.48	5.28	9.42;31.54	0.577	0.001*	0.600 (0.537)
IC activation contralateral side	0.60	0.28	0.21; 1.17	0.315	0.043*	
BMI	-0.53	0.26	-1.08;0.01	-0.306	0.053	
Men						
	Single-leg squat (n=28)					
Gmed activation	8.18	4.30	-0.69;17.05	0.319	0.069	0.402 (0.328)
IC activation injured side	-21.76	11.09	-44.65;1.12	-0.330	0.061	
BMI	-0.36	0.16	-0.68; -0.04	-0.377	0.028*	
	Single-leg hop for distance (n=25)					
BMI	-0.68	0.26	-1.22;0.14	-0.448	0.015*	0.200 (0.171)

B=unstandardized coefficient, SE=standard error, CI=confidence interval, β=standardized coefficient, IC=Iliocostalis, BMI=body mass index, bold characters=significant association. * indicates a significant association.



a)
SLS
Decent End
Ascent Start
D.Peak.Flexion
B.Peak.Flexion
A.Peak.Flexion
Knee Flexion (degrees)
100
80
60
40
20
0
-20
0
0.5
1
1.5
2
2.5
3
Time (Sec.)



b)
SLS
Decent End
Ascent Start
D.Peak.Abduction
B.Peak.Abduction
A.Peak.Abduction
Knee Abduction (degrees)
30
20
10
0
-10
-20
-30
0
0.5
1
1.5
2
2.5
3
Time (Sec.)

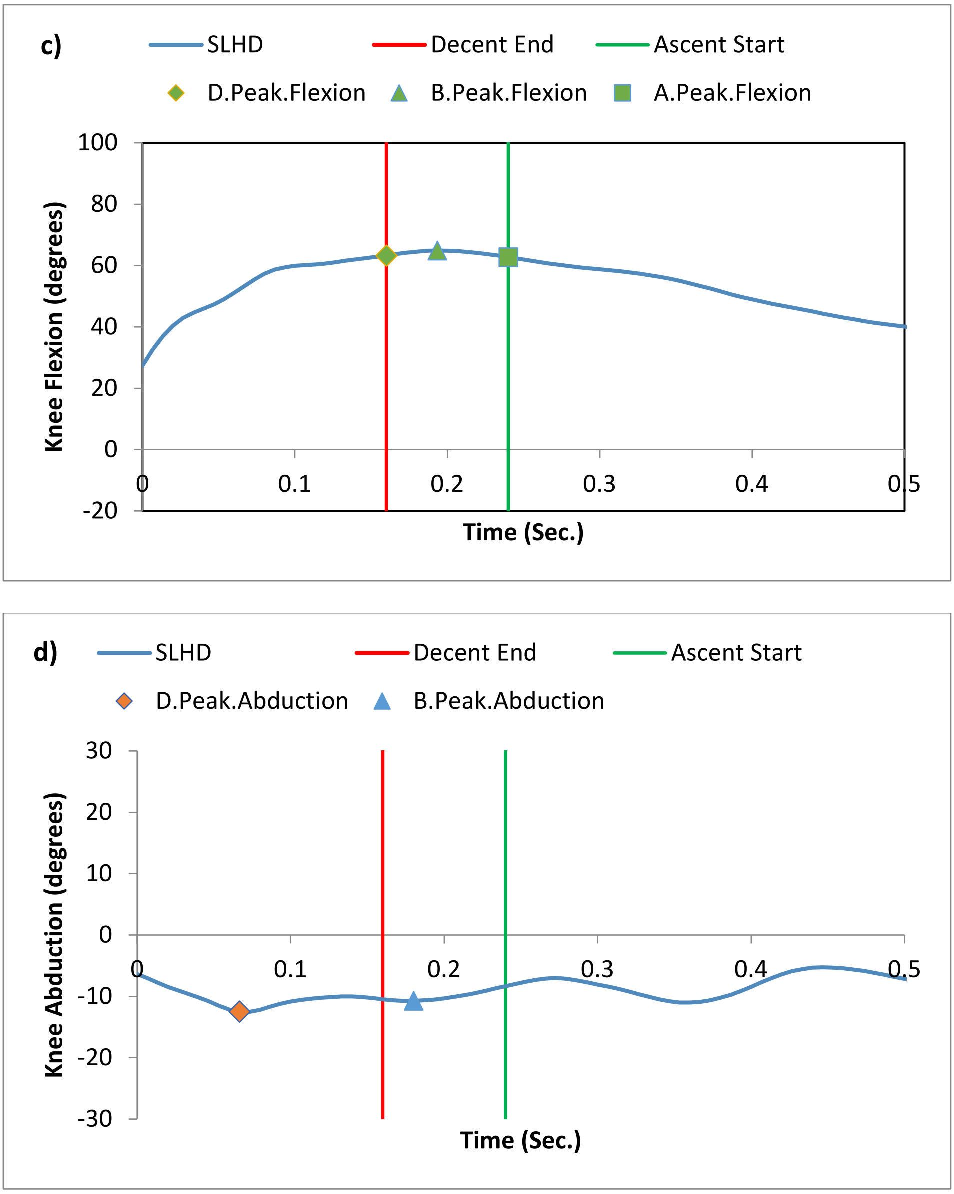


Figure 2a-d. Example of peak knee flexion and peak knee abduction versus time for the single-leg squat (SLS) and the single-leg hop for distance (SLHD). D=descent phase, B=bottom phase, A=ascent phase