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Motor control after anterior cruciate ligament reconstruction

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Chapter 3

Abnormal Landing Strategies after ACL Reconstruction

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ABSTRACT

The objective was to analyze muscle activity and movement patterns during landing of a single leg hop for distance after anterior cruciate ligament (ACL) reconstruction. Nine (six males, three females) patients six months after ACL-reconstruction (ACLR) and 11 (eight males, three females) healthy control (CTRL) subjects performed the hop task. Electromyographic signals from lower limb muscles were analyzed to determine onset time before landing. Biomechanical data were collected using an Optotrak Motion Analysis System and force plate. Matlab was used to calculate kinetics and joint kinematics. Side-to-side differences in ACLR and CTRL subjects as well as differences between the patients and CTRL group were analyzed. In ACLR limbs, significantly earlier onset times were found for all muscles, except vastus medialis, compared with the uninvolved side. The involved limbs had significantly reduced knee flexion during the take-off and increased plantarflexion at initial contact. The knee extension moment was significantly lower in the involved limb. In the CTRL group, significantly earlier onset times were found for the semitendinosus, vastus lateralis and medial gastrocnemius of the non-dominant side compared with the dominant side. Muscle onset times are earlier and movement patterns are altered in the involved limb six months after ACLR.

INTRODUCTION

Successful anterior cruciate ligament (ACL) reconstruction in terms of restoring the anterior laxity of the knee joint to near-normal values does not automatically mean restoration of normal knee function.[1] For example, only 31% of patients after ACL-reconstruction (ACLR) regain a normal walking pattern one year after surgery.[2] Biomechanical analysis of hop tasks revealed persistent altered knee joint moments > one year after ACLR.[3] Recent research has shown that the results of hop tests can be used as predictors of short-term dynamic stability in subjects with ACL-deficient (ACLD) knees.[4] These tests are appealing as they are easy to perform, simulate in part sport-specific demands and have satisfactory reliability.[5]

In several papers studying high demand activities of the ACLR knee, substitutions of moments were shown to occur from the knee to the hip or ankle.[6,7] The data suggest that the patients used a strategy by transferring the moments from the knee to the hip and/or the ankle in order to reduce the knee moment. The studies cited above, however, lack the incorporation of electromyographic (EMG) data during the hopping tasks.[3,6,7]

If functional deficits last more than one year after surgery, it is reasonable to assume that deficits are even more pronounced six months after surgery. Thus, if hop tests are used as indicators of the functional performance of patients after ACLR, it is imperative that a comprehensive assessment that includes kinematic, kinetic and EMG-analysis is conducted in order to better understand the biomechanical and neuromuscular profiles.

EMG analysis is a method that offers a partial insight into neuromuscular activity. The onset of muscle activity before landing is particularly of interest because it increases the stiffness of the joints.[8] This feed-forward mechanism is important as it allows the muscles time to generate force to provide correct lower extremity alignment during landing. Insufficient timing may place the knee in an unfavorable position, increasing the risk of sustaining an ACL (re)injury. So far, research on muscle onset during hop tasks have been performed in ACLD patients or in patients more than one year after reconstructive surgery.[9-11] Muscle onset patterns of patients six months after ACLR, at which time return to sports is commonly allowed, are currently unknown.

The purpose of this study was, therefore, to assess the bilateral lower limb joint kinematics and kinetics and onset time of EMG activity during the single leg hop test in patients after ACLR during the single leg hop for distance. These data will be compared with a CTRL group.

MATERIAL AND METHODS

Subjects

Nine consecutive patients after ACLR (six males and three females) with a mean age of 28.4 ± 9.7 years were measured 27 ± 1.5 weeks post-operatively. Eleven healthy subjects (eight males and three females) with a mean age of 26.3 ± 5.5 years were used as CTRL. All subjects were level I–II athletes. Level I sports are described as jumping, pivoting and hard cutting sports. Level II sports also involve lateral motion, but with less jumping or hard cutting than level I.[12] Inclusion criteria for the patients were: isolated ACL lesion, no major meniscal or cartilage lesion, normal limb alignment as determined on a standardized lower extremity x-ray and defined as an anatomical femoro-tibial axis of between 2° and 7° of valgus and no varus as well as no relevant previous surgery at any other joint of the limbs. Exclusion criteria were joint effusion, varus thrust of the knee, >50% removal of the width of the base of the meniscus, grade 3 rupture of the collateral ligaments, concomitant ligament injuries to the posterolateral or – medial corner, traumatic or degenerative cartilage lesions <2 cm^2, surgical procedures or injuries to contralateral limb or any history of neurological, vestibular or visual impairment. An arthroscopically assisted, iso-anatomical two-incision, bone-patellar tendon-bone (BPTB) technique by the same surgeon was performed on all patients.[13] All patients followed the same rehabilitation program at the same institution, consisting of immediate weight-bearing, range of motion (ROM) exercises, stationary bicycle training and closed-chain strengthening and coordination exercises. Running was permitted after 12 weeks, progressing to agility and sports-specific drills. Return to unlimited sports was allowed after nine months. The patients completed the IKDC Subjective Knee Evaluation Form and were examined on the test day according to the IKDC Knee Examination Form.[14] Laxity testing was performed using the Rolimeter device (AIRCAST Europe, Freiburg, Germany). The medical ethics committee of the University Medical Center Groningen approved the study protocol, and all subjects signed an informed consent before the measurements started.

Single leg hop test

All subjects performed a single leg hop for distance keeping their arms behind the back, and maintained their balance for at least 1s after landing.[15] About 5–10 practice trials were performed to familiarize the subjects with the hop task. All subjects subsequently carried out three maximal trials for each limb and they were instructed to jump as far as possible. The subjects were allowed to use their preferred landing technique. The hop was deemed correct by the experimenter if the subject was able to achieve maximal hop distance while maintaining balance for at least 1s after landing. Limb symmetry in the ACLR group was calculated by: (maximum hop distance involved limb/maximum hop distance uninvolved limb × 100). The limb symmetry index in the CTRL group was calculated by: (maximum hop distance dominant limb/maximum hop distance non-dominant limb × 100). In the CTRL group, the dominant limb was defined as the one with the furthest hop distance.

The maximum hop distance was used to determine the correct take-off position for each limb and was marked with tape on the floor. From this take-off position, the subject was instructed to land onto the centre of the force plate. Maximum distance was used to maximally challenge the dynamic stability of the knee for this task.[16] It was demonstrated in recent research that using the maximal hop test results in a high ability to discriminate between the hop performance of the involved and the uninvolved side both in patients with an ACL injury and in patients who have undergone ACLR.[15] All subjects jumped wearing their own sport shoes. Ten correct recordings were obtained for each limb. All subjects took a standardized rest period of 1 min after the third and sixth jump.

Biomechanics

The set-up for collection of biomechanical data has been described previously and will be summarized here briefly.[17] A 3D motion analysis system (OPTOTRAK® Northern Digital Inc., Waterloo, California, USA) with two cameras was used for the acquisition of kinematic data by detecting reflective markers placed on the pelvis and limbs. Sample frequency was 150 Hz. During six phases of the hop, the joint angles for the hip, knee and ankle joints were recorded; phase 1): initiation of take-off, phase 2): moment of toe off, phase 3): flight phase, phase 4): is where initial contact was made on the force plate, phase 5): landing with full body weight; and phase 6): 1s period after initial contact. ROM was operationalized as the difference between the minimum and maximum joint angles and was calculated for the take-off phase and the landing phase.

The kinetic variables that were evaluated included vertical end horizontal ground reaction force (GRF) and joint moments. The GRF was normalized to body weight and moments were normalized for body weight × limb length to make comparison between subjects possible. All analyses for moments and angles were performed in the anatomical sagittal (*xy*) plane and are counted as positive for flexion angles and extension moments. All positive ankle angles are plantar flexion angles. The start of rise in the vertical GRF was used to determine the first instant of the landing. The support moment (M_s) was calculated according to Hof:[18]

$$M_S = ½\,M_{hip} + M_{knee} + ½\,M_{ankle} = qF_p$$

The kinematic and kinetic variables were imported and calculated in the Matlab (The Mathworks Inc., Natick, Massachusetts, USA) toolbox in BodyMech (BodyMechGuide

3.06.01, Version 2006, http://www.bodymech.nl). A biomechanical analysis was performed on all patients. Unfortunately, we lost part of the biomechanical data in the first four patients as marker recognition was erroneous due to daylight in the lab. Hence, due to an incomplete set of data and insufficient number files, a statistical analysis could not be performed. Owing to time restrictions of the principal investigator, more patients could not be included for the current paper.

EMG

EMG data of the following limb muscles were recorded: gluteus maximus (GM), biceps femoris (BF), semitendinosus (ST), semimembranosus (SM), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), gastrocnemius medial and lateral head (MG and LG) and soleus (SO). After skin preparation, disposable surface electrodes (Neotrode®, Conmed Corporation, Utica, New York, USA) with a 10 × 10 mm electrode area were placed with an interelectrode distance of 20 mm. The electrode pair was positioned in the longitudinal direction of the muscle fibers in accordance with SENIAM guidelines.[19] EMGs were recorded with a PORTI (Twente Medical Instruments, Enschede, the Netherlands) physiologic data logger, which was connected by a fiber-optic cable to the computer. Pre-amplifier specifications were >110 dB common mode rejection, <2 µV RMS noise level and >500 MΩ input impedance. The pre-amplified EMGs were sampled at 800 Hz and high-pass filtered at 20 Hz with a third-order digital Butterworth filter. The force plate signal was sampled at 750 Hz and used for the kinematic and kinetic analysis. An analogue trigger circuit was connected to the vertical GRF output, using a trigger level of approximately 100 N. This trigger signal was recorded, together with the EMGs, on the EMG recording device. The latter had a sampling frequency of 800 Hz, but was asynchronous with the kinematic data acquisition. For the detection of the onset times τ, the “approximated generalized likelihood ratio” (AGLR) was used.[20] In this test, the ratio (variance after $t=\tau$)/(variance before $t=\tau$) is determined for all possible values of τ over a sensible interval. The value of τ at which the logarithm of this ratio is maximal is selected as the most probable onset time. Identification of this point allowed to differentiate between activity shortly after take-off and the preparatory activity before landing. The latter was of interest in this study and was defined as onset time.

In our experiments, we first calculated the smoothed (10 Hz zero-lag Butterworth filter) rectified EMG. The square of two × its minimum value over the interval (0.5–0 s) before landing was taken as the “variance before.” The start of the “sensible interval” was the interval before landing over which the smoothed rectified EMG remained below three × the minimum value. The duration of this interval was 1 s. The onset time is the continuous rise in EMG activity as defined by the algorithm, indicating the build-up of muscle activity preparing for landing.

Statistical analysis

The mean onset times of the EMG signals for each muscle were calculated. Differences between uninvolved and involved limbs in the ACLR and differences between dominant and non-dominant limbs in the CTRL group were analyzed using the Wilcoxon signed ranks test. The Mann–Whitney test for independent samples was used to analyze leg differences in onset times between ACLR and CTRL groups, α-levels were set at < 0.05 for statistical significance. For each kinematic and kinetic variable, mean values from five jumps were compared between the involved and the uninvolved limbs of all patients. The mean difference was used for statistical analysis with a non-parametric Wilcoxon signed ranks test.

RESULTS

IKDC

The mean subjective IKDC score for the ACLR was 81 ± 7.1. The objective IKDC score revealed that one patient had an A, seven had a B and one patient scored a C (donor site pain on palpation). Mean laxity showed <2 mm side-to-side difference. All patients had negative Lachman and pivot shift test results. Meniscus lesions were found in all patients, equally divided in four medial and four lateral meniscus lesions, all requiring partial meniscectomy. In one patient there was a combined lesion of the medial meniscus + grade II chondral lesion of the medial femoral condyle.

Hop index

The mean limb symmetry index for the CTRL was 95.5. The mean distance of the dominant limb was 143.0 ± 6.8 cm vs 136.8 ± 5.7 cm of the non-dominant limb. The limb symmetry index for the patients was 83.8, with a mean distance for the involved of 93.7 ± 19.2 cm and 111.7 ± 8.2 cm for the uninvolved limbs, respectively.

Biomechanics

Kinematics

The involved limbs had significantly reduced knee flexion during the take-off phase and more plantar flexion in the ankle at initial contact when compared with the uninvolved side. Knee ROM of the involved limb was significantly decreased during take-off in comparison with the uninvolved side. There was a trend that ROM was decreased for the hip and ankle joint in the involved limb during take-off. During the landing phase, there was a trend that ROM was decreased for the hip and knee joint and increased in the ankle joint of the involved limb compared with the uninvolved side (Table 1).

Table 1. Mean hip, knee and ankle angles (SD) of the involved and uninvolved limb for each hop phase of all subjects. These phases are: 1 = before take-off, 2 = take-off, 3 = flight, 4 = initial contact, 5 = landing, 6 = 1 sec after initial contact. Range of motion (SD) of the involved and uninvolved limb during take-off (ROM1) and landing (ROM2). ROM angles for take-off are the differences between joint angles of phase 1 and phase 2. ROM angles for landing are the differences between joint angles of phase 4 and phase 5.

Hop phases	Hip			Knee			Ankle		
	Uninvolved (SD)	Involved (SD)	p	Uninvolved (SD)	Involved (SD)	p	Uninvolved (SD)	Involved (SD)	p
1	65.7 (16.9)	75.7 (41.4)	0.90	61.9 (6.6)	50.6 (5.7)	0.04	-23.3 (5.0)	-15.9 (10.2)	0.08
2	8.3 (4.45)	13.5 (5.2)	0.08	24.9 (5.3)	26.5 (6.4)	0.50	16.0 (4.6)	12.7 (12.6)	0.80
3	32.6 (7.6)	31.5 (3.9)	0.90	54.2 (4.2)	49.9 (7.0)	0.08	15.6 (6.7)	23.1 (12.0)	0.30
4	51.7 (10.4)	46.6 (6.9)	0.50	16.1 (3.8)	14.8 (4.7)	0.70	0.4 (2.7)	15.9 (13.4)	0.04
5	71.1 (9.4)	59.5 (11.4)	0.08	58.4 (7.5)	46.6 (6.4)	0.08	-3.4 (3.9)	3.6 (13.2)	0.70
6	52.3 (13.5)	42.6 (18.4)	0.10	32.9 (11.5)	31.2 (12.1)	0.70	-2.7 (3.1)	2.3 (17.1)	0.90
ROM take-off	57.6 (20.0)	62.2 (11.4)	0.08	37.0 (8.8)	25.3 (4.9)	0.04	39.3 (7.9)	28.4 (5.6)	0.08
ROM landing	18.8 (6.2)	13.7 (7.0)	0.20	42.3 (5.1)	31.3 (7.3)	0.08	5.7 (2.1)	13.3 (11.0)	0.30

Kinetics

The horizontal GRF was significantly lower in the involved limbs compared with uninvolved limbs (Table 2). There was no significant difference between limbs for vertical GRF.
The mean knee extension moment was significantly lower in the involved limb. Hip extension and ankle plantarflexion moments were increased on the involved side, but not statistical significant. The support moment was significantly lower for the involved limbs. Compensation for the reduced knee extension moment was primarily made at the ankle joint.

Table 2. Mean normalized peak ground reaction force (GRF), peak internal hip, knee, ankle and support extensor moments in landing, standard deviation (SD) and significance level.

	Mean uninvolved (SD)	Mean involved (SD)	p
Horizontal GRF (N/BW)	0.89 (0.23)	0.74 (0.26)	0.01
Vertical GRF (N/BW)	2.17 (0.23)	2.24 (0.36)	0.80
Hip (Nm/BW/limb length)	0.25 (0.07)	0.29 (0.08)	0.90
Knee (Nm/BW/limb length)	0.30 (0.03)	0.17 (0.05)	0.04
Ankle (Nm/BW/limb length)	0.12 (0.03)	0.14 (0.03)	0.10
Support moment (Nm)	0.37 (0.03)	0.30 (0.01)	0.04

The observation that the horizontal GRF is lower in the involved limb can partly be clarified by a biomechanical analysis of the movement, using a 2D 8-segment model with turning joints.[21] The inverse dynamics simulation was performed on a particular jump on an involved limb, that is: the joint angles, velocities and accelerations were derived from the recordings. The ground contacts and the GRF were calculated from forward dynamics simulation (Figure 1(a)).[21] In a second simulation, the movement of the swing of the lower limb was reduced during landing, so that its foot would not pass the stance foot (Figure 1(b)). From this simulation, it appeared that the horizontal component of the GRF was reduced in the first simulation by the ongoing swing of the lower limb compared with the second simulation. As can be seen from Figure 1(a), the distance between the GRF and the knee joint is kept very small, indicating a low knee extensor moment. This indicates that the landing strategy incorporates the swing limb in keeping knee extensor torques limited. It also suggests that the adapted movement control pattern covers at least both limbs.

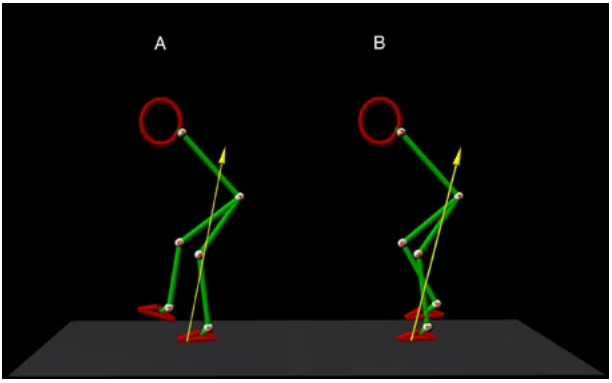

Figure 1. Landing phase of the involved limb derived from a 2D simulation. The effect of the contralateral swing limb is shown. The line shows the attachment point and direction of the ground reaction force (GRF). (a) The swing limb passes the stance limb resulting in distance of the GRF close to the knee joint. This results in a lower knee extension moment. (b) The swing limb remains behind the stance limb resulting in a distance of the GRF further away from the knee joint. The knee extension moment is increased.

EMG

Onset times

EMG onset times in patients of the GM, BF, ST, SM, VL, RF, MG, LG and SO muscles were significantly earlier in the involved limb (Table 3). The earlier onset time for the VM was, however, not significantly different in the involved limb. EMG onset times in healthy subjects of the different muscles did differ significantly between dominant and non-dominant sides, except for the ST, VL and MG, which were significantly earlier in the non-dominant limbs. Differences in EMG onset times between the involved and the uninvolved side in the ACLR group were significantly larger than differences between the dominant and the non-dominant side in CTRL group, except for the ST, VL and VM (Table 3). Most muscles in the uninvolved side had later onset times when compared with the involved side in patients after ACLR.

Table 3. Means and differences in means in EMG onset times (ms) of healthy subjects (dominant and non dominant limbs) and of patients (uninvolved limbs and involved). Differences between limbs were compared between healthy subjects and patients. Abbreviations: (GM) gluteus maximus, (BF) biceps femoris, (ST) semitendinosus, (SM) semimembranosus, (VM) vastus medialis, (VL) vastus lateralis, (RF) rectus femoris, (MG and LG) gastrocnemius medial and lateral head and (SO) soleus.

Muscles	Uninvolved leg patients (SD)	Involved leg patients (SD)	Mean difference uninvolved -involved limb patients (SD)	*p*	Dominant leg controls (SD)	Nondominant leg controls (SD)	Mean difference dominant - non-dominant limb controls (SD)	p	Mean difference controls – patients	*P*
GM	76.4 (34.4)	124.6 (20.7)	-48.2 (37.5)	0.02	106.3 (23.6)	103.0 (25.4)	-3.3 (9.4)	0.10	-51.5	0.001
BF	90.7 (40.2)	119.7 (24.0)	-28.9 (35.2)	0.02	91.4 (20.6)	95.6 (17.0)	4.2 (15.5)	0.30	-24.7	0.01
ST	95.0 (41.0)	120.8 (19.7)	-25.8 (33.1)	0.04	105.8 (14.6)	110.7 (14.5)	4.8 (8.8)	0.03	-21.0	0.80
SM	90.8 (38.7)	124.4 (15.3)	-33.6 (33.0)	0.01	101.4 (19.6)	107.2 (15.5)	5.8 (15.5)	0.30	-27.8	0.01
VL	70.9 (37.3)	90.6 (18.4)	-19.7 (65.5)	0.02	91.6 (29.5)	100.7 (32.4)	-9.1 (19.5)	0.04	-10.5	0.30
VM	73.1 (39.4)	110.8 (16.3)	-37.7(39.8)	0.10	95.1 (28.6)	112.8 (27.7)	-17.7 (19.6)	0.30	-20.1	0.50
RF	58.1 (25.1)	83.5 (12.3)	-25.4 (31.0)	0.02	70.7 (17.9)	66.5 (10.3)	-4.2 (18.4)	0.40	-29.6	0.01
MG	46.7 (27.8)	86.7 (42.0)	-40.0 (36.0)	0.03	62.2 (17.3)	64.4 (17.5)	2.2 (14.3)	0.04	-37.8	0.006
LG	55.1 (34.3)	103.5 (20.9)	-48.4 (30.5)	0.01	61.9 (15.7)	65.7 (13.8)	3.8 (11.1)	0.10	-44.6	0.05
SO	50.0 (21.2)	101.0 (17.0)	-51.0 (24.1)	0.01	59.9 (13.7)	61.2 (11.5)	1.3 (7.1)	0.10	-49.7	0.002

DISCUSSION

Six months after ACLR, muscle onset times of the GM, VL, RF, BF, SM, MG, LG and SO 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. These findings are in agreement with a study showing that muscle pre-activity increases the sensitivity of the muscle spindles, allowing joint perturbation to be detected more quickly.[22] Patients in the current study appear to utilize a distinctive feedforward control strategy that enhances joint stability. In fact, this was found in the biomechanical part of this study that was conducted on five of the nine patients reported. The patients had decreased knee flexion angles and moments at landing in the involved limb. Hence, the patients stiffened the involved limb before and during landing. These findings reinforce the fact that preparatory muscle activity results in increased joint stability.[23] Stability in this respect is the state of a joint remaining or promptly returning to proper alignment through an equalization of forces.

Earlier onset times of the hamstrings were noted in the current experiment. Earlier activity of the BF has also been reported during a drop jump.[10] Unfortunately, these authors reported only the total mean time of both limbs; hence, the contribution of the involved limb could not therefore be discerned from their results. Others have not found differences in the EMG activity of the hamstrings when comparing patients after ACLR with uninjured subjects during a single leg hop.[24] The explanations for the differences could be the time between surgery and the jump task, EMG analysis technique and gender of subjects.

The VL and RF had earlier onset times in the involved limb, which is in agreement with others, but again only the total means of both limbs in patients after ACLR were reported in that study.[10] Earlier EMG onset time of the LG of the involved limb found in this study has been reported in female ACLR and in patients with ACLD[9,25] In general, it is remarkable that patients after ACLR had earlier EMG onset times. The patients after ACLR in this paper had shorter jump distances, and yet had earlier EMG onset times outside the normal values as demonstrated in CTRL. They fired the muscles sooner relative to the time of landing. We want to reiterate how we defined muscle onset time: the first burst in EMG as detected by Staude and Wolf algorithm before landing. This definition is in agreement with others.[26] The rise in muscle activity has been shown to be timed relative to the expected time of landing and not the point of take-off.[26] Visual estimation of the jump distance might provide the necessary input to predict jump and scaling of the muscle activity. In case the jump distance was increased, the onset of EMG remained practically the same relative before landing. Sensorimotor memories of the dynamic interactions between the body and the environment have been shown to provide a robust mode of motor control. It may be that patients have adapted, based on the negative experiences such as giving way of the knee before surgery, or modified their motor programming, e.g., by limiting the amount of flexion in the knee upon landing. Before landing, they demonstrated a general co-contraction of the muscles to “tense up” before foot contact occurred in an attempt to increase the stability of the knee.[27] Interestingly, muscle onset in most muscles of the uninvolved limb of the patients after ACLR was in fact later when compared with the CTRL group. We can only speculate on this finding. Perhaps, the patients after ACLR had ineffectively timed neuromuscular firing before sustaining the ACL injury. Although speculative, this is an issue of concern, as late muscle onset might increase the risk of ACL injury.[28] Recently, subjects with an ACLD knee who experience instability of the knee during daily activities or sports have been classified as non-copers.[29] These non-copers have abnormal movement patterns of the knee as well as altered neuromuscular control.[30] Presumably, although the patients had surgical reconstruction of the ACL, they still show some typical muscle activity patterns that have been reported in non-copers.[31,32] The patients after ACLR as well as non-copers utilize a stabilization strategy, that stiffens the knee joint. Another possibility is that the adaptations in fact were learned early in the rehabilitation to protect the donor site. It may require more time than the six months after the reconstruction to “reprogram” the neuromuscular system. The present results are in agreement with other reports following ACLR, indicating that the movement patterns are altered during functional tasks and these last beyond the time frame when return to sports is allowed.[3,6,7,33-35] Paterno and co-workers showed that female patients after ACLR had higher vertical GRF on the uninvolved side during a drop vertical jump.[35] In other words, patients loaded their uninvolved side more than the involved side until a mean of 27 months after surgery. Residual asymmetries at a mean time of 7.2 years after ACLR were also found in another cohort of female ACLR.[34] They reported greater co-contraction ratios of the hamstrings–rectus femoris and decreased peak anterior–posterior shear force during a drop jump in comparison with healthy subjects. Considering that injury risk is increased five-fold soccer players after ACLR in comparison with uninjured players,[36] rehabilitation programs may need to be extended or revised to prevent recurrent injury.

The number of patients available for this study was limited to nine. Before this study, a power analysis could not be conducted based on the literature due to absence of numerical data,[9] data for both involved and uninvolved limbs were grouped into one figure,[10] or data from the involved limb of patients with ACLD[11] were reported. The strength of the limb muscles had not been tested in this study. This limitation is of minor influence, because quadriceps strength has only a low correlation to hopping performance after ACLR.[37]

The sole use of the single limb hop test for distance to decide whether return to high demand sports is safe for patients after ACLR may be questioned. The patients did not fulfill the demanded limb symmetry of >85% as one of the criteria to return to sports as proposed in the literature.[38] The mean maximum hop limb symmetry was 83.8 and was based on maximum distance achieved and not on the average of three hops. It has been shown from the literature that average results from the hop test underestimate the potential in patients.[5,39] Patients show an increase in jump distance as trials progresses. They even improve jump distance from trial to trial, which is not seen in healthy controls.[39] Secondly, it was demonstrated in a recent research that using the maximal hop test results in a high ability to discriminate between the hop performance of the involved and the uninvolved side both in patients with an ACL injury and in patients who have undergone ACLR.[15] One should keep in mind that our patients had been treated with a BPTB technique; it is possible that the results might differ had a different ACL graft been used. It is recognized that the hop task as used in this study is a pre-planned activity, but was chosen for its high reliability.[5] On the other hand, it would be interesting to repeat a jump task experiment with patients after ACLR under unanticipated or fatigued conditions to simulate normal athletic activity. It has been shown that unanticipated cutting tasks lead to a non-specific co-contraction of the muscles to increase joint stiffness.[40] This phenomenon is basically what patients in the current study demonstrated. Recently, Wilkstrom et al. demonstrated altered muscle onset times in jump trials in which subjects were not able to maintain balance upon landing.[41] Their paper indicated that successful jump landing required an earlier muscle activity in order to land safely.

Perspectives

It is remarkable that, although anterior laxity has been (nearly) restored, patients after ACLR still utilize muscle recruitment patterns to increase the stiffness of the knee similar to patients with ACLD knees.[42] Movement patterns in the involved limbs were also significantly different from uninvolved limbs. Moreover, they do this by including the control of the swing leg during landing, according to our biomechanical simulations. The asymmetries in muscle onset and movement patterns may predispose to re-injury of the ACL. Future studies with a prospective and longitudinal design should focus on whether and how these asymmetries may change over time and whether they can be improved by rehabilitation. Furthermore, sensitive tests should be developed to determine a safe return to sports.

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