Neuromuscular activity during stair descent in ACL reconstructed patients: a pilot study

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Abstract

Background: The anterior cruciate ligament (ACL) rupture is a severe knee injury. Altered kinematics and kinetics in ACL reconstructed (ACL-R) patients compared to healthy participants (ACL-I) are known and attributed to an altered sensorimotor control. However, studies on neuromuscular control often lack homogeneous patient cohorts. The objective was to examine neuromuscular activity during stair descent in patients one year after ACL reconstruction.

Method: Neuromuscular activity of vastus medialis (VM) and lateralis (VL), biceps femoris (BF) and semitendinosus (ST) was recorded by electromyography in ten ACL-R (age: 26±10 years; height: 175±6 cm; mass: 75±14 kg) and ten healthy matched controls (age: 31±7 years; height: 175±7 cm; mass: 68±10 kg). A ten-minute walking treadmill warm-up was used for submaximal normalization. Afterwards participants descended ten times a six-step stairway at a self-selected speed. The movement was separated into pre-activation (PRE), weight acceptance (WA) and push-off phase (PO). Normalized root mean squares for each muscle, limb and movement phase were calculated. Kruskal-Wallis ANOVA compared ACL-R injured and contralateral leg and the ACL-I leg ($\alpha=0.05$).

Results: Significant increased normalised activity in ST during WA in ACL-R injured leg compared to ACL-I and during PO in VL in the ACL-R contralateral leg compared to ACL-I. Decreased activity was shown in VM in ACL-R injured compared to contralateral leg ($p<0.05$).

Conclusion: Altered neuromuscular activations are present one year after ACL reconstruction compared to the contralateral and healthy matched control limb. Current standard rehabilitation programs may not be able to fully restore sensorimotor control and demand further investigations.

Keywords: Knee, neuromuscular control, sensorimotor control, electromyography, rehabilitation

1 Introduction

The anterior cruciate ligament (ACL) rupture is a common sports injury which is followed by short-term and long-term effects such as pain, limited mobility, reduced sports participation and finally joint degeneration. To prevent an early onset of degenerative knee osteoarthritis the surgical reconstruction is still very often the treatment of choice [1], despite similar outcomes for conservatively or surgically treated ACL patients [2,3].

It is already stated in many different studies that kinematic and kinetic analysis show differences regarding movement patterns during walking, running or jumping in participants with ACL deficiency or reconstruction still years after rehabilitation [4–6]. These differences can also be seen in normal activities of daily living, as a systematic review and meta-analysis found some evidence that patients with reconstructed ACL (ACL-R) had lower external knee flexion moments during stair descent compared to controls and the contralateral leg. Furthermore, trends are shown that the ACL reconstructed knee had lower varus moments compared to the contralateral limb but not compared to controls [7]. This indicates that, after ACL reconstruction and rehabilitation, the movement pattern is not fully restored. Several articles and reviews reporting high reinjury rates after reconstruction and return to sport also confirmed this fact which points out a possible lack in the surgical or conservative treatment of ACL injuries, rehabilitation scheme itself or insufficient compliance to it [8,9].

It is assumed that the loss of the ACL and its incorporated receptors emerges into an altered sensorimotor control [10–12]. Additionally, pain can be a substantial factor influencing neuromuscular control, that results predominately in inhibiting mechanisms [13,14]. The sensorimotor control implements the interaction between the sensory input (afferent), the processing of the information and the output (efferent) as a motor behaviour, which can be measured e.g. biomechanically [15]. Hall and colleagues [16] showed that the neuromuscular activity in ACL-R patients during stair descent was significantly higher in the M. gluteus maximus, medius and M. semimembranosus. Moreover, these patients showed a reduced activity in the M. rectus femoris compared to the control group. These results underline the previously described indication of an altered neuromuscular control. Nevertheless, the research group included a broad range of patients with time after surgery from 1-18 year. This limits the interpretation of neuromuscular deficits towards a specific time point of for example return to full sport participation.

To the authors knowledge Hall et al. [16] published the first study investigating the neuromuscular activity in ACL-R patients during stair walking. Stair ambulation is a complex activity of daily life and demands during stair descent high levels of movement control. Moreover, it applies more load to the body and the lower extremity compared to level walking [16]. Therefore, the aim of this cross-sectional pilot study was to examine the neuromuscular activity in ACL-R participants one-year post surgery during stair descent. The hypothesis was that the ACLR participants show lower quadriceps and higher hamstring activity compared to healthy controls. Furthermore, it is expected that one-year post-surgery no differences are present between the injured and the contralateral side. The results should contribute to the knowledge about specific neuromuscular consequences after ACL rupture and reconstruction during activities of daily living and should lead to more insights into the neuromuscular deficits after an ACL injury.

2 Material and method

2.1 Participants

In total, twenty participants were included in this study. Ten participants (ACL-R) suffered one year (13.6±2 months) prior to the study from an ACL rupture. All patients were recruited from the same hospital and treated with a quadriceps tendon graft by the same surgeon. This surgeon was also in charge of the clinical examination before inclusion. The participants had additional injuries which needed surgery, such as suture of the meniscus (N=5), partial tear of the medial collateral ligament (N=3), partial meniscectomy (N=1) and one had no additional injuries.

Ten healthy participants (ACL-I) without prior injury of the knee were selected as controls. They were matched according to age, height, weight, gender, (sports) activity level and leg dominance. General inclusion criteria were: Age between 18 and 65 years, physically active (Tegner Activity Score (TAS) = min. 4) [17] and ACL status intact or reconstructed. Exclusion criteria for both groups were: cardiac, neurological, peripheral and vascular diseases, musculoskeletal disorders, acute infection, acute pain, effusion, other acute lower limb/trunk injuries, thrombosis, alcohol abuse and pregnancy.

All participants complete a questionnaire regarding their quantity of weekly sports participation (sports discipline and time spent), the Knee injury and Osteoarthritis Outcome Score (KOOS) with a subscale asking for pain, other symptoms, function in daily living, function in sport and recreation and knee related quality of life [18], the TAS with a score range from 0 (sick leave or disability pension) to 10 (competitive sport on professional level) [17] and a visual analogue scale (VAS) [19] (0–10 cm) describing the general well-being (gwb) and acute pain. The study was ethically approved by the local legal authority.

2.2 Procedures

After providing informed consent and filling out the questionnaires, participants were prepared for electromyographic (EMG) measurements. The skin was shaved, roughed with sandpaper and cleaned with alcohol for optimal detection of the muscle signals. The electrodes were attached on the M. vastus medialis (VM) and lateralis (VL), M. biceps femoris (BF) and M. semitendinosus (ST) of both limbs and a reference electrode was placed on the right patella according to the recommendations of SENIAM [20]. Bipolar electrodes (Blue Sensor®, Ambu, Denmark, Type P-00-S, inter-electrode distance: 20 mm) were used and the inter-electrode impedance was controlled and kept equal or below 2 kΩ (Impedance meter D175, Digitimer®, Herfordshire, UK). Transmission of the signal occurred across a differential-preamplifier (gain: 500, Input Impedance: 4000 M, Common Mode Rejection 90 dB at 60 Hz) to a telemetric main amplifier (PowerPack, Pfitec®, Endingen, Germany; Band-Pass Filter: 10 Hz - 1 kHz, gain: 5.0, resultant overall gain: 2500), where it was recorded at 2000 Hz. An analogue/digital conversion was conducted (NI PCI 6255, National Instruments®, Austin, USA; 1.25 MS/s, 16 Bit), before a labVIEW®- based software (Imago Record, Pfitec®, Endingen, Germany) registered the signals.

A 10-minutes warm-up on a treadmill (hp cosmos®, QUASARmed, Nussdorf-Traunstein, D) at a speed of 5 km/h (1.39 m/s), preceded the measurements to prepare participants for the upcoming protocol: First they walked on the same treadmill with same speed for three minutes, whereby electromyographic signals were recorded in the last minute. The treadmill was equipped with two force transducers (Typ KMB52, 10KN, Megatron Elektronik AG & Co. KG, Putzbrunn, Germany) underneath it to detect the initial heel strike of each gait cycle. During post-processing these recordings were used for individual submaximal EMG normalization of each subject [21].

After the warm-up and measurement for normalization, the participants performed the stair climbing task. They descended 10 times at a self-selected speed a six-step stairway. Two multi-component force plates (Type 9286BA, Kistler®, Winterthur, CH) were embedded in the third and fourth step. They were supported by a heavy metal frame independent from the stairs. The participants had to start always with the right foot, to have the same limb on the third, respectively fourth force plate to detect the initial foot contact. The inclination of the stairway was 30.6° with a step height of 17.1 cm and step depth of 29 cm [22].

2.3 Data analysis

Stair descent movement cycles were divided into three movement phases: pre-activation (PRE), weight acceptance (WA) and push-off (PO). The pre-activation phase was defined from 150 milliseconds prior to initial foot strike until foot strike [23]. The next phase, weight-acceptance (WA), lasted from initial contact to the transition from braking to propulsion phase as indicated by the posterior-anterior force component (horizontal force). Form there until the last recorded force level (toe-off), the push-off phase (PO) was set [24].

Electromyographic data was further processed using a labVIEW®-based Software (Imago Process Master, Pfitec®, Endingen, Germany). The raw EMG signal were band-pass filtered at 10-500 Hz (Butterworth, 2nd order) and the root mean squares (RMS) for each phase and muscle was calculated and exported in an Excel spread sheet. The mean activation of each muscle during the complete gait cycle (mean out of 50 single cycles) from normal walking was used for (submaximal) normalization of the three phases during stairway walking. This secured comparability of individual results between injured and contralateral limb as well as between injured limb and matched leg from controls. For the ACL-I control group the left or right leg was used according to the injured side of the matched ACL-R participant.

Furthermore, the average and standard deviation of the 10 single trails in each participant were calculated and checked for plausibility. Individual values higher than twice the standard deviation were tracked back to the original data and corrected if possible. The average of the individual trails was used as correction value.

2.4 Statistical analysis

The data was checked for normal distribution using the Shapiro-Wilk Test, revealing a deviation from normal distribution, however for a better comparison with other studies the data is also presented with means and standard deviations. The participant characteristics (age, height and weight) were test for significant differences using an independent t-test. A Kruskal-Wallis ANOVA was conducted for the ACL-R injured and contralateral leg and ACL-I matched leg for the three different movement phases (PRE, WA & PO) and the four recorded muscles (SPSS software version 23.0, IBM, SPSS; Inc. Chicago, IL, USA, 2015). Additionally, a Dunn-Bonferroni post-hoc pairwise comparison was performed if the previous conducted ANOVA showed a significant difference. The α-level was set at 0.05.

3 Results

An independent t-test comparison of the anthropometric data and participant characteristics revealed no significant differences of the ACL-R and ACL-I group (p>0.05) except for the KOOS (p=0.001). The ACL-R group showed a reduced total score of the KOOS (approx. -10 % of total KOOS) compared to the ACL-I control group. The VAS asking for pain was similar in before and after measurement and the VAS regarding the general well-being was slightly increased in both groups after protocol completion. A TAS of averaged 6 (range from 4-9) in the ACL-I group indicate a higher recreational sports activity in the disciplines of e.g. soccer, basketball, tennis or jogging up to 5 times per week. The ACL-R participants with a TAS of averaged 7 (range from 5-10) were lightly more active, with participation in competitive sports in e.g. tennis, athletics, basketball and orientation run. Further details of the participant characteristics can be found in table 1.

Table 1: Baseline characteristics of participants. Legend: Knee Injury and Osteoarthrosis Outcome Score (KOOS); Visual analogue scale (VAS) for acute pain (pain) and general well-being (gwb) pre/post measurement: indicates values on a 0-10 cm scale; Tegner activity score (TAS) (pre-injury) range from 0 (sick leave or disability pension) to 10 (competitive sport on professional level).

Characteristics	**ACL-I (N=10)**	**ACL-R (N=10)**	***p-value***
Age – years	31 ± 7	26 ± 10	0.29
Height – cm	175 ± 8	175 ± 7	0.97
Weight – kg	68 ± 10	75 ± 14	0.29
Female (%)	30	30	
KOOS (max. 100)	98 ± 1	88 ± 4	0.001

VAS - pain pre/post (max.10)	0.1 / 0.7	1 / 1	0.14 / 0.53
VAS – gwb pre/post (max. 10)	0.7 / 0.9	2 / 4	0.36 / 0.19
TAS (max: 10)	6 ± 1	7 ± 2	0.10

The comparison of neuromuscular activity during stair descent of the ACL-R injured and contralateral leg and the ACL-I matched control leg revealed significant differences of the groups in three conditions. Significant differences were found during the WA in the semitendinosus muscle, post-hoc analysis resulting in a significant higher activity of 61 % in the ACL-R injured leg compared to the ACL-I matched leg (p=0.047) (see table 2). Furthermore, statistically significant differences were also observed in the vastus medialis and vastus lateralis muscles during the PO phase (p=0.007, p=0.008, respectively) (fig 1). The post-hoc analysis showed for the vastus medialis significantly reduced activities of about 70 % in the ACL-R injured leg compared to the contralateral leg (p=0.008) (table 2). The vastus lateralis had significantly higher neuromuscular activation (approx. +63 %) comparing the ACL-R contralateral leg and the ACL-I matched leg (p=0.006) (table 2). Additional details of the mean and standard deviation of the neuromuscular activity of each muscle in the three movement phases can be found in table 2.

Table 2. Normalized neuromuscular activity (Mean and standard deviation in % of the submaximal voluntary contraction (subMVC)) of the ACL-R injured and contralateral leg and ACL-I matched control leg. Legend: ACL-R= ACL reconstructed group; ACL-I= ACL matched control group; VM=vastus medialis; VL= vastus lateralis; BF= biceps femoris; ST= semitendinosus

Phase	**Muscle**	**ACL-R injured** (subMVC)	**ACL-R contralateral** (subMVC)	**ACL-I matched** (subMVC)	***p*-value**
PRE-ACTIVATON	**VM**	128 ±70	152±76	125±36	0.89
	VL	150±62	135±72	122±44	0.5
	BF	154±122	121±50	149±57	055
	ST	242±182	147±89	148±61	0.54
WEIGHT ACCAPTANCE	**VM**	275±95	256±131	270±138	0.81
	VL	290±187	186±31	215±82	0.2
	BF	70±46	113±57	64±34	0.09
	ST	158±110	120±60	61±55	0.03
PUSH OFF	**VM**	109±39	359±213	158±97	0.007
	VL	199±130	343±160	127±72	0.008
	BF	149±111	71±37	89±34	0.17
	ST	191±146	120±88	88±65	0.09

4 Discussion

The aim of this study was to investigate the neuromuscular activity during stair descent in patients one-year after ACL reconstruction. The neuromuscular activations during stair descent were normalised to recordings during treadmill walking at a self-selected speed. Results showed differences of the muscular activation comparing the ACL-R injured and contralateral leg and the ACL-I matched leg during the three movement phases. Specifically, higher normalised activities of the ST during WA in the ACL-R injured leg compared to ACL-I control leg, reduced neuromuscular activities of the VM of the ACL-R injured limb compared to the contralateral leg and higher activation of the VL of the ACL-R contralateral leg in the PO phase compared to ACL-I control leg differed significantly. These results partly confirm the hypothesis of lower quadriceps and higher hamstring activity in the ACL-R participants compared to the matched control leg.

The KOOS described in the participant characteristics show that the ACL-R participants are still functionally affected by the ACL injury, but can complete the movement tasks without greater decline or increase of the general well-being or pain, respectively. Furthermore, the TAS with a range from 5-10 indicates a return to high physical activity, also to competitive sports. These findings are comparable to a systematic review and meta-analysis revealing that the majority of ACL patients following ACL reconstruction return to some kind of sport, 63 % returned to their preinjury level and less than the half returns to competitive sport [25].

The recorded higher neuromuscular activation of the hamstrings during the weight acceptance can also been found in the study by Hall [16]. A significant higher activity of the semimembranosus muscle was found during 1-50% of stance phase during stair descent compared to the control group [16]. A study focusing on the kinetics during stair ambulation comparing the ACL-R injured to the contralateral limb found significantly lower peak knee flexion moments from weight acceptance until push off (complete stance) during stair descent in the leg with ACL reconstruction surgery [26]. Taking the primary purpose of the ACL – to prevent an extensive anterior tibia translation during extension – into account, higher activities of the hamstring muscles point to a supportive adaptation of the synergistic muscles in favour of the reconstructed ACL [27]. Thus, rehabilitation might not only focus on the recovery of quadriceps strength (knee extension) but also on the strengthening and neuromuscular control of the hamstrings.

Findings of significant reduction of the muscular activity in the VM during push off in the ACL-R injured limb are also indicated in other studies [16,26]. Concerning the injury mechanism of the ACL rupture with extreme knee valgus, this reduction might be a preventive act of adaptation against intense stress on the reconstructed ACL during movement. Furthermore, a reduced activity of the quadriceps might be a consequence of the surgical treatment with the quadriceps tendon graft. A study examining balance performance, isokinetic strength, squat jumps and stiffness in participants having a surgical repair of the ruptured ACL with a bone-patellar-bone tendon graft or semitendinosus/gracilis autograft, showed only significant differences in squat jump height comparing both groups one year after surgery [28]. However, insights into neuromuscular adaptations of the respective surgical techniques would complete the knowledge about the particular consequences.

The significantly higher activation of the VL and greater activation of the VM during PO in the contralateral leg compared to controls indicates a compensative strategy to ensure adequate function during movement [26]. Nonetheless, the higher activation might lead to an early onset of fatigue of the joint stabilizing muscles, which could explain high ACL rupture rates of the contralateral leg after the initial rupture [8].

Overall, the results of this study indicate and are in line with further conclusions that also years after surgery and complete rehabilitation, movement strategies and neuromuscular activation patterns may still be impaired in both limbs [29]. This might also be seen in the high reinjury rates after ACL rupture and reconstruction [2]. However, causes of reinjury rates are still not clearly identified. Different consequences in both limbs, as shown in this pilot study, do not support the general process of often used return to sport (RTS) criteria using limb symmetry indexes e.g. comparing quadriceps strength. A recent case control study supports this assumption with bilateral deficits in hop jumps comparing ACL reconstructed and healthy participants [30]. Furthermore, trends of higher hamstring activity during WA could lead to new orientation shifting the focus from pure quadriceps strength, representing a general aspect of physical function, to a more differentiated approach by analysing neuromuscular activity in physical function [31]. This may indicate the need of not only integrating strength of the hamstrings but also neuromuscular control of the hamstring in post-operative assessments since both aspects are important to support the function of the ACL graft after reconstruction. Additionally, a systematic review showed very inconsistent RTS strength criteria and isokinetic protocols to evaluate muscular strength [32]. Time until RTS is considered an important factor which is still discussed and investigated [33]. Thus, RTS guidelines are currently under revision pointing towards a multifactorial and optimized criterion-based RTS approach with a clear demand to include sensorimotor based criteria [34].

The demand to include sensorimotor based criteria is supported by the findings of the present pilot study and speaks in favour of an integrated rehabilitation process. A recent systematic review and multidisciplinary consensus points out the need of neuromuscular training to complete rehabilitation besides range of motion and muscular strength recovery [9]. Nevertheless, the neuromuscular approach might not be fully sufficient. First studies shift their attention from the outcomes of sensorimotor control (e.g. neuromuscular activity or biomechanical output) to the processing level (brain activity). Literature shows alteration in the cortical activation patterns, also years after ACL reconstruction and rehabilitation [35,36]. The ability of the brain to adapt morphologically and functionally to permanent changes is described as plasticity and provides a perspective to further explain the consequences of an ACL injury. Therefore, an ACL injury might not only be considered as a musculoskeletal but as a neurophysiological injury [37] and therefore more knowledge on central and peripheral adaptations is needed.

The study design with the integrated force plates underneath the stairway contributes to a standardised and precise analysis of initial contact and subsequent EMG data, however, there are some limitations. First, the participants could descent the stairs at a self-selected speed. This method can also be found in other studies [26,27] but might have a decisive impact on the recorded EMG activities during movement. Nonetheless, a standardised speed, for example with a metronome indicating when to take the next step, could highly modify the normal gait pattern of the participants. Furthermore, the submaximal normalization needs to be considered when comparing the results with other studies. Moreover, it is critically discussed whether the maximal voluntary isometric contraction (MVIC) measurement would have been the better option for EMG normalization. Literature has shown, that without training, the MVIC is reduced by 20-40 % compared to a trained MVIC. Also, the static contraction could lead to different results from the values recorded during movement, where the muscles move relatively to the skin [38]. Possible baseline differences during the reference task between cohorts and between extremities have to be kept in mind. Moreover, the used study protocol is in line with a previous conducted study measuring neuromuscular activity in participants with an acute ACL rupture and is therefore relevant for further comparisons [39]. The statistical analyses with the Kruskal-Wallis ANOVA was conducted to compare the muscles and movement phases of the groups. However, due to the small number of participants the statistically significant results need to be handled with caution. Nevertheless, different neuromuscular activity between the analysed legs of the participants during the three movement phases, especially in the quadriceps during the push-off phase in ACL-R contralateral leg (approx. 70 % increase), were quite substantial reaching sufficient clinical relevance. Moreover, a differentiation regarding the age groups might be reasonable as studies showed differences in EMG activities during walking and dynamic postural balance comparing young and elderly participants[40,41]. A further gender specific analyses of EMG data is warranted as soon as sufficient sample sizes per gender are measured, as studies on differences in kinematics and neuromuscular activity during single leg squats in healthy young participants indicate [42,43]. This is also highlighted by reported gender specific injury risk [44].

5 Conclusion

The neuromuscular activity comparing the injured and the contralateral leg of the ACL reconstructed group to a healthy matched control group differs during stair descent one-year after surgery. These preliminary results indicating towards higher hamstring activity in the ACL injured leg and higher quadriceps activation in the contralateral leg might point towards possibly changed sensorimotor control after ACL reconstruction and return to the activities of daily live and sports participation. More participants are needed to draw relevant conclusions, but the pilot results indicate the special importance of neuromuscular control mechanisms to further enhance rehabilitation and return to sports decisions. Analysis of neuromuscular activity by electromyography may serve as a valuable quality control tool to monitor this process.

6 References

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7 Figure 1

Figure1: Normalized neuromuscular activity (in % of the submaximal voluntary contraction (subMVC) comparing ACL-R injured and contralateral leg and ACL-I matched control leg. Displayed in a boxplot showing from top to down: outlier, upper extreme, upper quartiel, median, lower quartiel, lower extreme, outlier. Legend: PRE= pre-activation; WA= weight acceptance; PO= push off; VM=vastus medialis; VL= vastus lateralis; BF= biceps femoris; ST= semitendinosus.