SPORTS Orthopaedics and Traumatology

ORIGINAL PAPER

Sports Orthop. Traumatol. **35**, 158–165 (2019)

www.SOTjournal.com
https://doi.org/10.1016/j.orthtr.2019.04.002

Summary

Background: Studies showed altered kinematics and kinetics in anterior cruciate ligament (ACL) deficient participants, attributed to an altered sensorimotor control. However, literature on neuromuscular deficits is limited, thus the objective was to investigate the neuromuscular activity during stair ascent in patients with acute ACL rupture.
Material and methods: The activity of the M. vastus medialis (VM) and lateralis (VL), M. biceps femoris (BF) and M. semitendinosus (ST) was recorded using surface electromyography (EMG) in 9 acute ACL deficient (ACL-D) (rupture 1–3 weeks prior to test) and 9 ACL intact (ACL-I) matched subjects. Participants ascended 20 times a 6-step stair at self-selected speed. The movement was divided into pre-activation (PRE), weight-acceptance (WA) and push-off (PO) phase. Comparisons were made between the deficient leg of ACL-D and the matched uninjured leg of the ACL-I, as well as between the injured and non-injured leg of the ACL-D group.
Results: ACL-D showed in all muscles a reduced activation (ca. 50%, $p < 0.05$) compared to ACL-I during PRE. In ACL-D, quadriceps activity was also reduced (ca. 50%; $p < 0.05$) during WA, and hamstrings displayed a lower activation (ca. 35%; $p < 0.05$) during PO. Intragroup comparisons showed less consistent differences in all muscles and phases.
Conclusions: Altered activity during PRE indicates an alteration in the motor program (''pre-programmed activity''). Small differences in the intra-individual comparison showed bilateral consequences following ACL injury.
Level of Evidence: 3

Keywords
Anterior cruciate ligament – Sensorimotor control – Electromyography – Stair ascent

ORIGINAL PAPER

Neuromuscular control in patients with acute ACL injury during stair ascent – A pilot study

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Eingegangen/submitted: 27.11.2018; überarbeitet/revised: 03.04.2019; akzeptiert/accepted: 05.04.2019
Online verfügbar seit/Available online: 26.04.2019

Introduction

The rupture of the anterior cruciate ligament (ACL) is a common sports injury mainly affecting young and physically active persons. The ACL is often injured during cutting and pivoting sports like soccer, basketball and skiing. In over 70% the injury is caused by a non-contact mechanism due to high knee valgus stress and foot abduction [31,14]. The primary task of the ACL is to prevent anterior translation of the tibia in relation to the femur during static and dynamic movements and simultaneously excessive tibia rotation [21]. The injury can cause severe pain and often leads to surgical repair [17]. Moreover, a reduction in sports participation and/or a lower sports level, decreased quality of daily life and a higher risk for knee osteoarthritis are possible long-term consequences [13].

The surgical repair of the ACL with an endogenous tendon graft is a common treatment to prevent early knee osteoarthritis and to provide enhanced stability [20]. However, studies have shown a total secondary ACL re-injury rate of 15% (7% for the ipsilateral, 8% for the contralateral side) [31]. The high number of subsequent ACL injuries indicates that especially during sport participation, the stability of the knee is not fully restored and increases the risk of a reinjury [22]. Zult et al. (2017) described that difficulties in maintaining single-leg balance occurred in both legs up to two years after ACL reconstruction [34]. Yet, 20 years after injury and subsequent treatment, differences in movement strategies during a vertical hop test were found in ACL reconstructed and conservatively treated participants, as well as in contrast to healthy controls [19]. Several studies already investigated

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Neuromuskuläre Kontrolle bei Patienten mit akuter Ruptur des vorderen Kreuzbandes beim Treppeaufwärtssteigen – eine Pilotstudie

Zusammenfassung

Hintergrund: Studien zeigten bereits eine veränderte Kinematik und Kinetik bei Probanden mit gerissenem vorderem Kreuzband (VKB), die auf eine veränderte sensomotorische Kontrolle zurückzuführen seien. Die Literatur über neuromuskuläre Defizite ist jedoch begrenzt, weshalb das Ziel darin bestand, die neuromuskuläre Aktivität beim Treppenaufstieg bei Patienten mit akuter VKB-Ruptur zu untersuchen.
Material und Methoden: Die Aktivität der Muskeln Vastus medialis (VM) und lateralis (VL), Biceps femoris (BF) und Semitendinosus (ST) wurde durch Oberflächenelektromyographie (EMG) in 9 ProbandInnen mit einem akut rupturierten VKB (VKB-R) (Ruptur 1-3 Wochen vor dem Test) und 9 VKB intakten (VKB-I) ProbandInnen erfasst. Die Teilnehmer stiegen 20 Mal eine 6-stufige Treppe mit einer selbst gewählten Geschwindigkeit hinauf. Die Bewegung wurde in Voraktivierung (PRE), Gewichtsübernahme (WA) und Abstoßphase (PO) unterteilt. Es wurden Vergleiche zwischen dem verletzten Bein von VKB-R und dem entsprechenden gesunden Bein von VKB-I sowie zwischen dem verletzten und dem unverletzten Bein der VKB-R-Gruppe durchgeführt.
Ergebnisse: VKB-R zeigte in allen Muskeln eine reduzierte Aktivierung (ca. 50%, $p < 0{,}05$) im Vergleich zu VKB-I während der PRE. In VKB-R war während der WA auch die Quadrizeps-Aktivität (VM und VL) reduziert (ca. 50%; $p < 0{,}05$) und die Hamstrings (BF und ST) zeigten eine geringere Aktivierung (ca. 35%; $p < 0{,}05$) während des PO. Vergleiche zwischen den Gruppen zeigten weniger konsistente Unterschiede in allen Muskeln und Phasen.

kinematics and kinetics in patients with ACL repair or deficiency during activities of daily life (ADL) and showed altered movement strategies in these patients [8]. Most often, this is attributed to adaptations of neuromuscular activity due to changed sensorimotor control [29]. However, there are only few studies investigating neuromuscular alterations [24]. Trulsson et al. (2015) examined the neuromuscular activity in ACL deficient participants (2–11 months after rupture) during single and double leg squats. They showed differed neuromuscular activation, specifically lower activity in the involved limb compared to the non-involved leg [28]. Furthermore, Hall et al. (2015) found altered neuromuscular activity in ACL reconstructed participants (with a range from 1 to 18 years after surgery) compared to healthy controls during stair ambulation [9]. As a complex ADL, stair ambulation demands high levels of neuromuscular control. Moreover, higher knee joint moments during stair ascending occur compared to level walking, which requires a substantial amount of knee flexion and therefore sophisticated force generation [9]. As shown in the two previous described studies, the range between rupture or surgery and the conducted study is wide and not directly related to the injury itself and the early consequences of the ACL rupture. Thus, the objective of this pilot study was to investigate the neuromuscular activity during stair ascent in patients with an acute ACL injury. Based on literature focusing on the kinematic and kinetic outcomes after ACL rupture and reconstruction [8,9] the hypothesis was that the acute ACL injured participants would show a reduced quadriceps and enhanced hamstring activation compared to healthy controls.

Methods

Participants

Patients were eligible for this study when a pre-screening conducted by an orthopaedic surgeon (PH), specialized in knee injuries, pointed to an isolated ACL tear without any concomitant injuries (clinically tested and confirmed by magnetic resonance imaging (MRI)). Further inclusion criteria for the patients were as follows: no acute inflammatory signs, decreased swelling (<2 cm difference in the circumferential measurement compared to the contralateral side), no acute pain (Visual Analogue Scale (VAS) <5/10 [25]), approximately free range of motion (ROM, <20° difference to the contralateral side), able to walk on even ground and to climb stairs without any ancillary aids (such as crutches and orthoses). In total, nine patients with acute ACL rupture, meeting the described criteria were included. In addition, nine healthy matched controls were recruited. Superior inclusion criteria for both groups were: age between 18 and 65 years and physically active before injury occurrence (Tegner Activity Score (TAS) = min 4) [26]. Exclusion criteria included cardiac, neurological and vascular diseases, musculoskeletal disorders, acute infections, thrombosis, alcohol abuse and pregnancy. Furthermore, the participants completed a questionnaire regarding their type and duration of sports participation, the Knee injury and Osteoarthritis Outcome Score (KOOS) with subitems asking for pain, other symptoms, function in daily living, function in sports and recreation, and knee-related quality of life [23], the TAS (pre injury) with a score from 0 (sick leave or disability pension) to 10 (competitive sport on professional level) [26]

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Schlussfolgerungen: Veränderte Aktivität während der PRE deutet auf eine Änderung im motorischen Programm (Pre-programmed activity) hin. Geringe Unterschiede im intraindividuellen Vergleich zeigten bilaterale Folgen nach VKB-Ruptur.
Evidenzebene: 3

Schlüsselwörter
Vorderes kreuzband – Sensomotorische kontrolle – Elektromyographie – Treppensteigen

and VAS describing the general well-being (gwb) and pain, indicating values on a 0–10 cm scale. Baseline characteristics of the patients and healthy, matched controls are shown in Table 1.

Procedure

The study was approved by the local ethics committee (KEK No. 213/15). Written informed consent from the participants was obtained together with baseline characteristics.
Afterwards, the participants were prepared for surface electromyography (EMG) measurements. For the correct and optimal detection of the muscle activities, the skin areas according to SENIAM [11] were shaved, roughen with sandpaper and cleaned with alcohol prior to testing [1]. Bipolar electrodes (Blue Sensor®, Ambu, DK, Type P-00-S, inter-electrode distance: 20 mm) were attached on the M. vastus medialis (VM) and lateralis (VL), M. biceps femoris (BF) and M. semitendinosus (ST) of both limbs. Furthermore, a reference electrode was placed on the right patella according to the recommendations of SENIAM [11]. The inter-electrode impedance was checked and accepted at $\leq 2\,k\Omega$ (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, D; Band-Pass Filter: 10 Hz–1 kHz, gain: 5.0, resultant overall gain: 2500), where it was recorded at 2000 Hz for walking/stair ascent. 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, D) registered the signals.
Thus, the participants started with the warm-up and walked six minutes on a treadmill (hp cosmos®, QUASARmed, Nussdorf-Traunstein, D) at a speed of $5\,km\,h^{-1}$ ($1.39\,m\,s^{-1}$). The treadmill was equipped with two force sensors (Typ KMB52, 10KN, Megatron Elektronik AG & Co. KG, Putzbrunn, D) underneath it to detect the initial contact between foot and treadmill of each gait cycle. In the last two minutes of the warm-up, EMG signals were recorded and used for submaximal EMG normalization of each

Table 1. Baseline characteristics of participants with an intact ACL (ACL-I) and patients with a deficient ACL (ACL-D).

Characteristics	ACL-I (*N* = 9)	ACL-D (*N* = 9)
Age – years	29.88 ± 5.1	30.4 ± 7.8
Height – cm	174.1 ± 8.2	176.3 ± 6.8
Weight – kg	73.8 ± 7.8	70.1 ± 9.4
Female (%)	44.4	44.4
KOOS* (total max: 168)	166.1 ± 1.1	112.3 ± 28.2
VAS** – pain pre/post	0.11/0.27	0.76/1.36
VAS – gwb	0.7/0.74	0.9/1.34
Tegner score*** (max: 10)	5.1 ± 1.1	5.5 ± 1.6

*Knee Injury and Osteoarthrosis Outcome Score.
**Visual analogue scale: indicates values on a 0–10 cm scale.
***Tegner activity score (pre injury) range from 0 (sick leave or disability pension) to 10 (competitive sport on professional level); gwb = general well being.

participant individually during post-processing. After the warm-up, the participants fulfilled the stair climbing task. They ascended 20 times a six-step stairway at a self-selected speed. The self-constructed, wooden stairway had an inclination of 30.6° with a step height of 17.1 cm, a step depth of 29 cm [15] and was equipped with two integrated force plates (Type 9286BA, Kistler®, Winterhur, CH) on step three and four. The force plates were mounted on a rigid metal frame that is independent from the remaining stairway construction. The participants had to start always with the right foot first to have the same limb on the third and fourth step, force plates respectively. The situation is visualized in Fig. 1 and used in a preceding protocol [2].

Data processing

The neuromuscular activity of each muscle and limb during walking on the treadmill was calculated as a mean gait cycle from 50 single cycles and taken as 100%. This activity level was used for submaximal normalization of the neuromuscular activity during stair ascent. Ground reaction forces recorded by the two forces plates were used to divide the step ascent movement into three movement phases. The pre-activation phase (PRE) was defined as 150 milliseconds prior to the initial contact until initial contact [4]. 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). From there until the last recorded force level (toe-off), the push-off phase (PO) was set [15]. Afterwards the data was further processed using the labVIEW®-based Software (Imago Process Master, Pfitec®, Endingen, D). The raw EMG signals were band-pass filtered at 10-500 Hz (Butterworth, 2nd order) and the root mean square (RMS) values were calculated and exported. Afterwards, average stair climbing RMS values per movement phases were calculated out of 20 single stair ascents. Each averaged value was then divided by the submaximal mean value for submaximal normalization.

Statistical analysis

For the inferential analysis, the data was transferred to the statistical software JMP® (Version 10.0.0, SAS®, Cary, USA). Both groups were checked for normality using the Shapiro-Wilk test. A Mann–Whitney-*U* test was performed to compare the deficient leg of ACL-D and the matched limb of the healthy ACL-I as control. Moreover, an intragroup comparison examining the differences between the deficient leg and the contralateral limb of ACL-D was effectuated. The alpha level was set at 0.05.

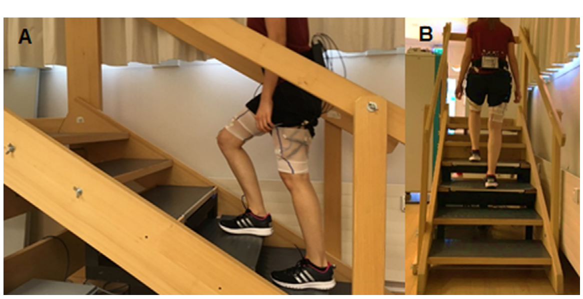

Fig. 1
Stair ascent. (A) Lateral view and (B) posterior view with force plates under steps 3 and 4.

Results

The comparison of ACL-D injured leg and ACL-I matched control limb revealed a reduction in the neuromuscular activity (approx. 50%) in all recorded muscles during PRE ($0.001 \leq p \leq 0.01$) in the participants with an ACL injury (ACL-D). The same reductions were found in the VM and VL ($p = 0.04$ and $p = 0.005$, respectively) during WA, whereas the hamstring muscle activity (ST and BF) was slightly reduced (approx. 16%, $p > 0.05$). In the PO phase, significant activity reductions were found in the BF and ST (approx. 35%, $p \leq 0.05$) but not in the quadriceps, VM and VL, respectively (Fig. 2).
The intragroup comparison of the ACL deficient leg and the contralateral side showed following results: during PRE and WA, a reduction in the VL and BF (approx. 29% in the ACL-D leg) were detected, but not in VM and ST. The reduced activity reached no significant difference except for the VL during WA ($p = 0.003$). An enhanced quadriceps activity (approx. 10%, $p \geq 0.05$) can be found in the PO phase in the ACL deficient leg whereas the BF and ST did not differ ($p \geq 0.05$) (Fig. 2).

Discussion

The objective of this pilot study was to investigate the neuromuscular activity in patients with an acute ACL rupture during stair ascent. The major result is a neuromuscular activity reduction of about 50% in the quadriceps (VL and VM) and hamstring muscles (BF and ST)

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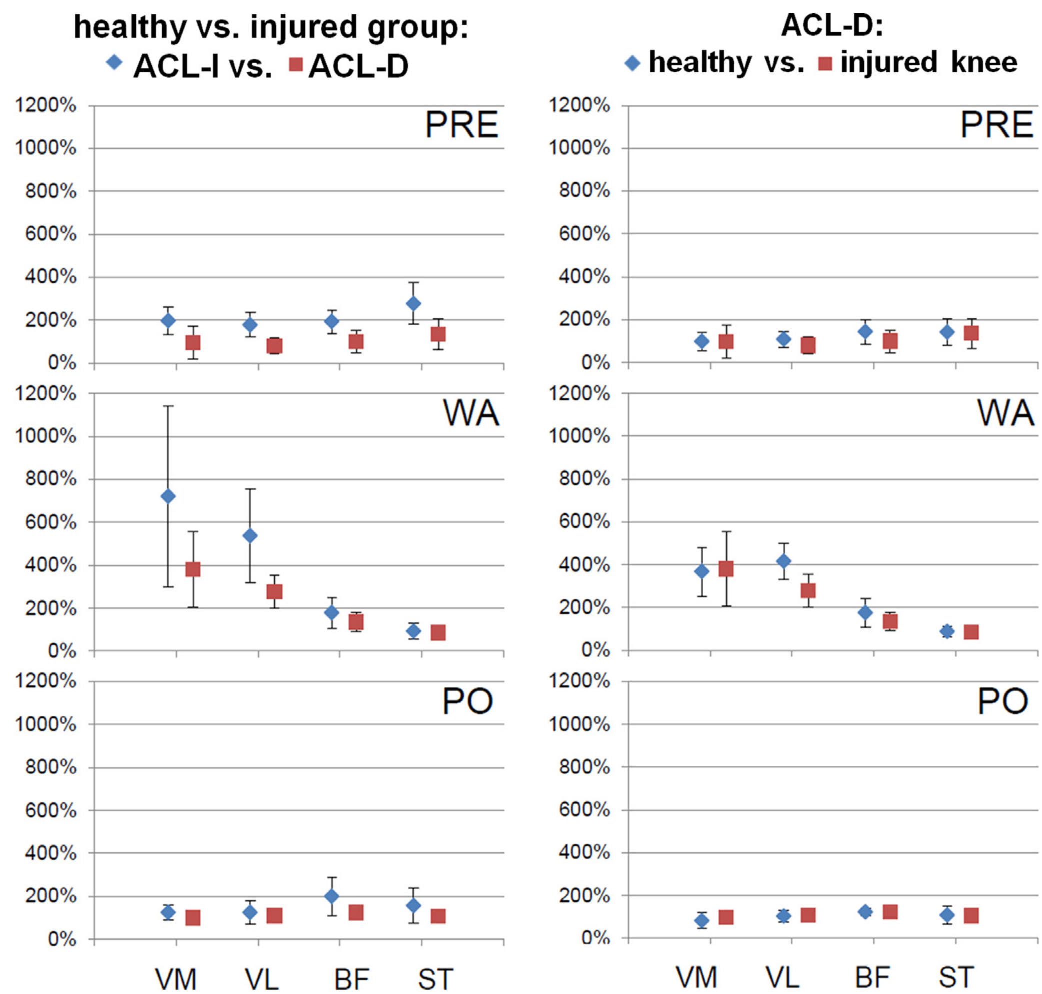

Fig. 2
Normalized neuromuscular activity (in %) comparing participants with an intact (ACL-I) and patients with a deficient ACL (ACL-D) and uninjured and injured knee of the ACL-D group respectively, in the different movement phases during stair ascent (PRE: pre-activation; WA: weight acceptance; PO: push-off; VM: vastus medialis, VL: vastus lateralis; BF: biceps femoris; ST: semitendinosus).

during pre-activation comparing the ACL deficient patients to healthy, matched controls. Additionally, a reduction of approx. 50% was found in the quadriceps during WA. The intragroup comparisons revealed less consistent results during all movement phases.

The findings of reduced neuromuscular activity especially in the quadriceps during WA is in line with the study by Goa et al. (2012). They showed that ACL-deficient patients (average 3 months post injury) had a significant extension deficit during stair ascent compared to healthy controls [6]. Further reductions in knee extension moments can be found in another study investigating the kinematics and kinetics of the knee and its surrounding muscles [33].

Reduced hamstring activation in the injured knee as detected during PO comparing ACL-D and ACL-I participants are supported by the study of Thambyah et al. (2004). They examined patients suffering from ACL deficient knees (average 8.5 months post injury) during stair ascent and found a reduction in peak external knee flexion moments comparing the involved limb of ACL patients with healthy controls [27]. In addition, the reduced hamstring activity can also be discussed in consideration partial contribution of the hamstring reflex activity in the specific time window WA [5]. However, there is only limited literature comparing the hamstring reflex activity in ACL-D and ACL-I participants, and is subject of further investigations [3]. Furthermore, Thambyah et al. (2004) showed reduced knee flexion moments also in the involved leg compared to the contralateral limb. Zult et al. (2017) confirmed the findings of Thambyah et al. (2004) by showing no overall impairment of the neuromuscular function in the contralateral limb. Their study revealed no altered neuromuscular activity levels approximately 5 months after the injury, except for voluntary quadriceps activation. Moreover, neuromuscular activation was impaired in both extremities during dynamic balance (Star Excursion Balance Test) [34]. These results are in contrast with the neuromuscular findings of the present study. The intragroup comparison showed similarities in the neuromuscular activity and it can be hypothesised that in the acute phase after an ACL rupture both limbs are almost equally impaired concerning the neuromuscular activation level. In addition, a systematic review focusing on the re-injury rates after initial ACL rupture and reconstruction found an injury rate of 8% of the contralateral side [31]. This might also point to bilateral consequences after unilateral ACL rupture. Thus, findings of altered neuromuscular function and kinematics, especially during dynamic balance and voluntary quadriceps activation, need to be further investigated. In addition, a recent guideline on rehabilitation after ACL rupture provides principals for all phases of the rehabilitation process [32]. However, it is still discussed whether especially limb symmetry indices are reasonable when assessing objective criteria throughout rehabilitation. A study by Hannon et al. (2017) showed significant reduced quadriceps strength capacity of the uninvolved limb (averaged 23 days after ACL rupture) compared to a dominant healthy control leg during a concentric contraction [10]. Thus, the uninvolved limb might not represent the condition of a healthy person and supports the findings in this pilot study. More studies are therefore necessary to further develop and proof evidence-based return to play criteria and associated guidelines [30].

The findings of a reduced pre-activation in all recorded muscles might be explainable regarding the sensorimotor control loop. Altered neuromuscular activities during PRE may be the result of the loss of neurosensory information eventually leading to an altered central movement program. Some research groups examining the central nervous system (CNS) reaction, postulated changes in the brain activity especially after ACL reconstruction [29,7]. The clear differences in the neuromuscular activity (reduction of 50% in ACL-D compared to ACL-I) in all recorded muscles during PRE imply that already either the injury itself leads to an immediate motor program change, or a short period between injury and measurements might cause an alteration of the movement program. In the future, further research should confirm the current findings and should focus more on the consequences on the CNS level after an ACL rupture. Furthermore, it should be taken into consideration to use the adaptive possibilities of the CNS regarding the prevention of a secondary injury during the rehabilitation process [9,12]. Additionally, the current results show bilateral consequences immediately after the rupture. This aspect might be used to start an early rehabilitation after the surgery by also training the non-injured leg aiming to achieve an effect in the injured leg as well. Here, bilateral learning and cross-education effects might need further consideration [18].

The current pilot study is a first attempt to investigate participants with an acute ACL rupture early after injury occurrence. However, a limitation was that the participants should be able to climb the stairs at self-selected speed. This method can also be found in another study by Gao et al. (2012) but has an impact on the recorded EMG activities during movement [6]. Nonetheless, a standardized cadence would change the normal gait pattern decisively. Moreover, analysis of contact time in healthy and injured leg and comparison of the injured group with the matched controls showed no statistically significant difference in contact time. The self-selected speeds are therefore comparable. Another point of discussion lays in the participant's inclusion criteria with the acceptance of an effusion in the knee with up to 2 cm circumference difference compared to the non-injured leg. The effusion might lead to quadriceps activation failure and could influence the neuromuscular activity especially in this early stage after injury. Yet, the relationship between knee joint effusion and quadriceps activation is under discussion [16]. Additionally, due to the small sample size, the inferential analyses can just be referred as a first impression. However, the small sample size is adequate for a (first) pilot study with mean group differences that imply clinical relevance.

Nevertheless, the results are opening new discussions and research fields for interdisciplinary approaches to better understand the short- and long-term consequences of an ACL rupture, especially on the neuromuscular level.

Conclusion

The present pilot study, investigating the neuromuscular activity in acute ACL deficient participants and healthy matched controls, revealed a reduced neuromuscular activation especially during pre-activation phase, indicating an alteration in the pre-programmed activity and in the underlying voluntary movement control pattern. Furthermore, neuromuscular control seems to be impaired in both extremities after unilateral ACL rupture. The findings need to be considered in rehabilitation settings. The results of the study warrant further research especially on the aspect of bilateral deficits after ACL injury and whether the contralateral leg can be considered an adequate reference for functional evaluation of the injured extremity. This eventually leads to evident and practically relevant recommendations for therapy, rehabilitation, training and prevention.

Conflicts of interest

There is no conflict of interest.

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