Journal Pre-proof

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PII: S0966-6362(20)30581-6
DOI: <https://doi.org/10.1016/j.gaitpost.2020.09.032>
Reference: GAIPOS 7924

To appear in: *Gait & Posture*

Received Date: 26 November 2019
Revised Date: 28 September 2020
Accepted Date: 30 September 2020

Please cite this article as: Annemie S, Sabine V, Filip S, Hilde V, Steven C, Jos V, Athletes with an ACL reconstruction show a different neuromuscular response to environmental challenges compared to uninjured athletes, *Gait and amp; Posture* (2020), doi: <https://doi.org/10.1016/j.gaitpost.2020.09.032>

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Athletes with an ACL reconstruction show a different neuromuscular response to environmental challenges compared to uninjured athletes.

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Word count: 4030 words

Highlights:

- Athletes with ACLR show higher hamstrings and lower vastus activation than controls
- This activation pattern might represent an arthrogenic muscle response
- Under cognitive loading hamstrings activation reduces in athletes with ACLR
- Athletes with ACLR show less neuromuscular adaptation when exposed to perturbations
- This reduced adaptation might be related with loss of afferent input after ACLR

ABSTRACT

Background

Evidence suggests that neuromuscular alterations in patients with an anterior cruciate ligament reconstruction (ACLR) are rooted in neurocognitive and proprioceptive deficits. The aim of this study was to assess neuromuscular control of athletes with ACLR under increased cognitive and environmental challenges.

Research question

Do athletes with ACLR show a different neuromuscular response to cognitive and environmental challenges relative to controls?

Methods

Cross-sectional study. Twenty athletes who had an ACLR (age: 23.7 ± 4.3 years, 14 males, time post-surgery: 258.6 ± 54 days) and twenty uninjured controls (age: 21.4 ± 1.5 years, 14 males) performed a stepping down-task in four environmental conditions: no additional challenges, while performing a cognitive dual-task, while undergoing an unpredictable support surface perturbation, and with the cognitive dual-task and unpredictable perturbation combined. Muscle activations of the vastus medialis (VM), vastus lateralis, hamstrings medialis (HM), hamstrings lateralis (HL), gastrocnemius medialis, gastrocnemius lateralis (GL) and gluteus medius were recorded with surface EMG. A three-way ANOVA with main effects for group, dual-task and perturbation was used to compare muscle activations.

Results

Athletes with ACLR show larger HM ($ES=0.45$) and HL activation ($ES=1.32$) and lower VM activation ($ES=0.72$), compared to controls.

Athletes with ACLR show a significantly smaller increase in VM ($ES=0.69$), VL ($ES=0.53$) and GL activation ($ES=0.52$) between perturbed and unperturbed tasks compared to controls. Furthermore,

under cognitive loading a significantly larger decrease in HM activation ($ES=0.40$) and (medial) co-contraction ($ES=0.75$) was found in athletes with ACLR compared to controls.

Significance

Athletes with ACLR show an altered neuromuscular response which might represent an arthrogenic muscle response. They show less additional adaptation to perturbed tasks compared to controls, potentially as result of altered proprioceptive input. Furthermore a larger influence of increased cognitive loading on the neuromuscular control was found in athletes with ACLR, indicating that also neurocognitive limitations may contribute to altered neuromuscular control.

Key words: ACL reconstruction; neuromuscular control; cognitive loads; perturbation; environmental constraints

INTRODUCTION

Many athletes with an anterior cruciate ligament reconstruction (ACLR) experience knee-instability[1], sustain a second anterior cruciate ligament (ACL) injury[2] and/or develop post-traumatic knee OA (PTOA)[3]. Prolonged deficits in neuromuscular control may play an important role in these long-term consequences[4–6].

Riemann et al.[7] defined neuromuscular control as “the unconscious activation of dynamic restraints (muscles) occurring in preparation for and in response to joint motion and loading, for the purpose of maintaining and restoring functional joint stability.” A well-coordinated neuromuscular control is the result of an optimal function of the entire sensorimotor system (e.g. provision of afferent information, subsequently the processing and integration of this information by the central nervous system (CNS) and ultimately the generation of an efferent motor response[7]). Deficits in neuromuscular control might thus have different underlying mechanisms. For example, the impaired sensory role of the ACL due to damage of ACL-mechanoreceptors after injury might cause alterations in neuromuscular

control[8]. In addition, the loss of proprioceptive afferent information might induce neuroplastic alterations of the CNS to compensate for the altered afferent input[9–11]. Furthermore, diminished ability of the CNS to process and integrate complex afferent information may also exist pre-injury, predisposing athletes for ACL injuries[9].

Although it is known that ACL injuries should not be seen as a ‘simple’ musculoskeletal injury but as a neurophysiological dysfunction[10], this is currently still under-addressed in ACL rehabilitation and return-to-sport (RTS) testing, which mainly focuses on restoring strength and landing patterns, often neglecting deficits in neuromuscular control and associated underlying neurocognitive deficits and central adaptations[12]. Returning to sport requires a complex integration of proprioceptive input by the CNS to constantly alter neuromuscular control to ensure dynamic knee stability in a rapidly changing environment while part of attention is allocated to the game and opponents. The added cognitive and environmental challenges may exaggerate neuromuscular deficits and increase re-injury risk.

Therefore, the aim of this study was to assess the influence of increased cognitive loading and unpredictable environmental challenges on neuromuscular control of athletes with ACLR. More specifically, we assessed how muscle activation levels change in athletes with ACLR and uninjured athletes when they are exposed to unpredictable platform perturbations and/or when they have to execute a dual-task while performing a stepping down task. We hypothesized that the injured leg of athletes with ACLR show altered activation levels of different lower limb muscles (quadriceps, hamstrings, gastrocnemius and gluteus medius) in response to environmental challenges, compared to healthy controls because of persistent underlying proprioceptive and/or neurocognitive deficits at time of RTS.

METHODS

Participants

Twenty patients with an ACLR (semitendinosus autograft) were included (see table 1). All patients played a sport that involves cutting, pivoting and/or jumping before their injury (minimum 2 training

days/week and 1 match/week (in-season)) and completed rehabilitation with their own physiotherapist and were cleared by their surgeon and/or physiotherapist to fully participate in training sessions again. The testing took place maximum two weeks before or after the first full training session (average time post-surgery: 8.5 ± 1.8 months). Furthermore, twenty uninjured athletes who were matched for age, gender and type of sport (see table 1) were included in the control group. The control subjects were free of lower extremity or back injuries for at least six months and had no history of ACL injuries. The participants signed a written informed consent and the study was approved by the local ethics committee with reference number S60182.

Protocol

After a standardized warming-up consisting of five minutes running and a set of hopping tasks, all participants performed a stepping-down task under different environmental challenges.

1. Stepping-down task without environmental constraints (NORMAL)

The participants were instructed to step off a 0.1m high box, land with 1 leg on a force plate and stand on this leg for 5 seconds (see figure 1). The force plate was embedded within a six degrees-of-freedom moveable platform (CAREN, Computer Assisted Rehabilitation Environment platform, Motekforce Link, Amsterdam, The Netherlands). This system allows one to induce preprogrammed base of support perturbations in a reliable and consistent way[13].

2. Stepping-down task combined with cognitive dual-task (DUAL)

A cognitive dual-task was added to the stepping down-task. The words blue, red, yellow, and green, surrounded by a colored frame were displayed on a screen in front of the participants when they approached the force plate. Participants were asked to say out loud the font color if the meaning of the word and frame color were similar, if they did not match, they had to say 'false'.

3. Stepping-down task combined with unpredictable base of support perturbations (PERT)

The participants were informed that unpredictable base of support perturbations could occur in one out of three stepping trials in a random order. The perturbation was programmed in D-

flow (D-flow, Motek Medical, Amsterdam, The Netherlands) based on a sine-wave input[14].

Lees et al.[15] showed that the CAREN System is highly reliable for consistently reproducing movement patterns of sine wave or ramped perturbations. The amplitude, direction and velocity of the perturbation were based on our previous work[13]. We used a multi-planar perturbation that simulates the ACL injury mechanism: a posterior and lateral translation (inducing knee abduction) combined with a rotation around the anterior-posterior axis (inducing a foot pronation) and a rotation around the vertical axis (inducing external rotation).

4. Stepping-down task combined with cognitive dual-task and unpredictable base of support perturbations (PERTDUAL)

This task is a combination of the two previous tasks (PERT + DUAL).

All tasks were performed on both the left and right leg. NORMAL and DUAL were performed seven times on each leg. PERT and PERTDUAL were performed twenty-four times on each leg as we wanted to induce eight perturbations on each leg (and only one out of three trials was perturbed).

Only the last three valid trials of all tasks were used for further data-analysis as pilot data showed that a learning effect exists that disappears after three trials. Trials were considered valid if the participant could maintain his/her balance for five seconds after landing without shuffling on the stance leg.

Data collection

GRF data was recorded by two 0.8x0.3m force plates (AMTI, Watertown, USA) sampling at 1000 Hz. Furthermore, muscle activity was simultaneously recorded with a wireless EMG system, type: Cometa Mini Wave (Zerowire, Aurion, Milan, Italy) at 1000Hz. The activation of the following muscles was measured: vastus medialis (VM), vastus lateralis (VL), hamstrings medialis (HM), hamstrings lateralis, gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and gluteus medius (GlutMed). Surface EMG electrodes (Ambu Blue Sensor, Ballerup, Denmark) were placed according to the SENIAM guidelines[16]. Three static maximal voluntary contractions (MVC's) of five seconds for all muscle groups were performed in the beginning of the test session to normalize EMG signals. The detailed MVC setup has been described in a previous study[17].

Data analysis

Data processing was undertaken in Visual 3D (v.6.01.07, C-Motion, Germantown, USA) and MATLAB (R2017a, The MathWorks, Nattick, USA). A 4th order low-pass Butterworth filter with a cut-off frequency of 18 Hz was used to filter forces. Initial contact (IC) events were created using a 10N threshold of the vertical GRF.

Raw EMG signals of the MVC's and the different stepping-down tasks were bandpass filtered (6-240Hz), rectified, and low-pass filtered with a 4th order zero-lag Butterworth filter at a cut-off frequency of 15 Hz. Subsequently, integrals were calculated over a period from 50ms post IC until 250ms post IC. This period was selected as it represents compensatory postural adjustments based on existing literature[18]. For the MVC trials integrals were calculated for the 200ms-period with the highest activation. Afterwards, the integrals of the stepping down tasks were normalized by the maximal integral obtained during the isometric MVCs. Finally, co-contraction indices (CCI) were calculated according the following equations:[19]

- $CCI = (HM + HL) / (VM + VL) * (HM + HL + VM + VL)$
- Medial CCI = $(HM / VM) * (HM + VM)$
- Lateral CCI = $(HL / VL) * (HL + VL)$

For the dual-task, an accuracy score was calculated by calculating the percentage of correct answers. Similarly, for the perturbations the percentage of successful trials was calculated (e.g. no shuffling or stepping response of contralateral leg).

Statistical analysis

All statistical analyses were performed in SPSS (IBM SPSS Statistics Version 25.0, New York, USA). For every parameter, 2 separate three-way ANOVAs were performed:

A) A between-groups analysis with the following three factors:

1. Group (ACL injured leg vs. control group)
2. Perturbation (unperturbed vs. perturbed trials)
3. Dual-task (no dual task vs dual task).

B) A between-legs analysis with the following three factors:

1. Leg (ACL injured leg vs. ACL uninjured leg)
2. Perturbation (unperturbed vs. perturbed trials)
3. Dual-task (no dual task vs dual task).

The control group consisted out of 20 legs. Per control subject, 1 leg was selected and we included the same amount of dominant and non-dominant legs as in the group of athletes with ACLR to reduce the possible influence of leg dominance. The dominant leg was defined as the preferred leg to kick a ball.

If a significant interaction effect was found, post-hoc comparisons were performed to further assess the interaction effect (details about all statistical steps can be found in Supplementary File 1). Furthermore Cohen's D effect sizes were calculated with $d=0.2$ considered as a 'small' effect size, 0.5 represents a 'medium' effect size and 0.8 a 'large' effect size. Since this study is an explorative study, no adjustment for multiple testing was performed. This strategy avoids increasing the risk for false negatives (type II errors) which is desirable in explorative studies but one should be aware that this also has the disadvantage of increasing the risk for false positives (type I errors)[20,21]. Therefore, we want to stress that the results of this study are all explorative and need to be confirmed by other studies.

The main aim of this study was to investigate whether the ACL injured leg of athletes with ACLR respond differently to environmental challenges compared to uninjured controls (factor group) and compared to the contralateral leg (factor leg). Therefore, we primarily focused on significant two- or three-way interaction effects which include the factor group or leg. Results that do not include a group or leg effect, are outside the scope of this paper and can be found in Supplementary File 2. Considering that group and leg were critical factors in our analyses, we will first describe the main effects for group (neuromuscular differences between the ACL injured leg and the control group) and main effects for leg (between-leg differences in the ACL group) before addressing interaction effects.

A power-analysis was performed to determine the sample size, based on previous EMG studies conducted in our laboratory and by others (Briem et al. 2016, KSSTA). For an ANOVA with 3 factors that all have 2 levels and 20 observations per condition, we predict a power of 0.7-0.9 to detect a three-way interaction-effect that has a medium effect size (ES=0.50).

RESULTS

Performance on cognitive dual-task and perturbation

No difference in accuracy on the dual-task and no difference in percentage of successful responses to the perturbations were found between groups and between both legs of the athletes with ACLR (see table 2).

Neuromuscular control

The muscle activation levels (mean IEMG) of the different lower limb muscles and the CCI's for the different groups (ACL injured leg, ACL uninjured leg and control group), during the different environmental conditions can be found in table 3.

Main effect for group (injured leg of athletes with ACLR vs. control group)

The ANOVA showed a group effect for VM ($p=0.042$), HM ($p=0.035$), HL ($p<0.001$), CCI ($p<0.001$) and lateral CCI ($p<0.001$) (table S2a of Supplementary file 2). The injured leg of athletes with ACLR has significant lower VM activation (7.5%) ($p<0.001$, ES=0.72), higher HM activation (6.5%) ($p=0.005$, ES=0.45) and higher HL activation (7.6%) ($p<0.001$, ES=1.32) compared to controls (VM:12.8%, HM=4.9%, HL=3.2%) ($p<0.001$, ES=0.72). Furthermore, the injured leg of athletes with ACLR showed higher CCI (26.5%) ($p<0.001$, ES=1.20) and higher lateral CCI (13.5%) ($p<0.001$, ES=1.34). compared to the control group (CCI:11.4%, lateral CCI: 13.5%).

Main effect for leg (injured vs uninjured leg of athletes with ACLR)

The ANOVA showed a leg effect for HL ($p=0.003$) and lateral CCI ($p=0.009$) (table S2b of Supplementary file 2). Athletes with ACLR showed higher HL activation in their injured leg (7.6%) compared to their

uninjured leg (3.5%) ($p < 0.001$, $ES = 0.79$). Furthermore, the athletes with ACLR showed larger lateral CCI in their injured leg (13.47%) compared to their uninjured leg (6.03%) ($p < 0.001$, $ES = 0.64$).

Group x perturbation interaction

The ANOVA showed a significant interaction effect between group and perturbation for VM ($p = 0.023$), VL ($p = 0.037$), GL ($p = 0.025$) activation and medial CCI ($p = 0.038$) (table S2a of Supplementary file 2). Post-hoc analyses clarified (figure 2) that controls show a significant larger increase in VM ($p = 0.005$, $ES = 0.69$), VL ($p = 0.031$, $ES = 0.53$), GL ($p = 0.043$, $ES = 0.52$) activation in response to perturbations compared to the injured leg of the ACLR group. Similarly, the controls show, a larger increase ($p = 0.047$, $ES = 0.48$) in medial CCI due to perturbation compared to the injured leg of the ACLR group.

Leg x perturbation interaction

The ANOVA showed a significant interaction effect between leg and perturbation for GL activation ($p = 0.031$) (table S2b of Supplementary file 2). Post hoc analyses clarified (figure 2) that the uninjured leg of athletes with ACLR shows a significantly larger increase in GL activation in response to perturbations compared to the injured leg of patients with ACLR ($p = 0.015$, $ES = 0.50$).

Group x dual-task interaction

The ANOVA showed an interaction effect between group and dual-task for HM activation ($p = 0.042$), CCI ($p = 0.007$) and medial CCI ($p = 0.036$) (table S2a of Supplementary file 2). Post-hoc analyses clarified (figure 3) that the injured leg of athletes with ACLR show a significant larger decrease in HM activation ($p = 0.015$, $ES = -0.58$), CCI ($p = 0.04$, $ES = -0.72$) and medial CCI ($p = 0.040$, $ES = -0.50$) when adding a dual-task compared to uninjured controls.

Leg x dual-task interaction

The ANOVA showed no interaction effects between leg and dual-task, for any of the assessed parameters (table S2b of Supplementary file 2 and figure 3).

Group x dual-task x perturbation interaction effect

Only for HM activation a significant three-way interaction effect was found ($p=0.040$) (table S2a of Supplementary file 2). To explain this interaction effect a two-way ANOVA was performed for the unperturbed and perturbed tasks separately (figure 4). This showed a significant interaction between group and dual-task during the unperturbed conditions ($p=0.003$), but not in the perturbed conditions ($p=0.774$). During the unperturbed trials, the injured leg of the ACLR group showed a significant decrease in hamstrings activation when a dual-task was added ($p=0.006$, $ES=0.75$), which was not found in the control group. While during perturbed tasks a significant decrease in HM activation was found in both groups (control: $p=0.001$, $ES=0.31$; ACL injured leg: $p=0.002$, $ES=0.36$).

Leg x dual-task x perturbation interaction effect

The ANOVA showed no three-way interaction effect between leg, dual-task and perturbation for any of the assessed parameters (table S2b of Supplementary file 2 and figure 4).

DISCUSSION

The aim of this exploratory study was to investigate whether the injured leg of athletes with ACLR show a different neuromuscular response compared to the contralateral, uninjured leg and compared to controls when exposed to environmental challenges. The primary analyses showed that the injured leg of athletes with ACLR demonstrate less adjustment in muscle activation levels (a smaller increase in VM, VL and GL activation) when exposed to unpredictable platform perturbations compared to uninjured controls (figure 2). Furthermore, increased cognitive loading had a larger influence on the muscle activation levels of the injured leg of athletes with ACLR compared to uninjured controls (larger reduction in HM activation and (medial) co-contraction) (figure 3). These findings confirm the hypothesis that the injured leg of athletes with ACLR show a different neuromuscular response to environmental challenges compared to uninjured controls. This study could not demonstrate clear between-leg differences in neuromuscular response to environmental challenges, in athletes with ACLR.

A neuromuscular response that might represent arthrogenic muscle response?

In general, we found that athletes with ACLR show higher HM and HL activation in their injured leg compared to the control group and higher HM activation in their injured leg compared to their uninjured leg. Furthermore, they showed lower VM activation in their injured leg compared to the control group. This altered neuromuscular pattern might represent an arthrogenic muscle response (AMR). AMR is a natural mechanism of reflex inhibition and/or facilitation of muscles surrounding an injured joint to prevent potentially detrimental movements[22]. In patients with an ACL injury, AMR has been shown to result in inhibition of the quadriceps (ACL antagonist) and increased excitability of the hamstrings (ACL agonist)[8] to protect the injured joint. It is believed that AMR in patients after ACLR is caused by a change in discharge of sensory receptors in the knee joint due to factors such as swelling, inflammation, joint laxity, but also due to damage of mechanoreceptors[22,23].

The combination of both low quadriceps and high hamstrings activation, explains why the athletes with ACLR of our study showed higher co-contraction in their injured leg compared to the control group. High co-contraction might be beneficial in the first weeks after injury and/or surgery as it can improve dynamic knee joint stabilization[24]. However, demonstrating high co-contraction in all situations and this for a longer term (such as beyond RTS), might be unfavorable as it might result in excessive loads on the articular cartilage potentially influencing the risk for PTOA[24].

Compensation for proprioceptive loss?

The athletes with ACLR showed less changes in muscle activation in their injured leg compared to controls, in response to perturbations. While the controls showed a clear increase in VM, VL and GL activation due to perturbations (figure 2), only a slight increase in muscle activation and medial co-contraction was found in the injured leg of athletes with ACLR during perturbed tasks. No clear between-leg differences were found (except for GL activation), indicating a bilateral altered neuromuscular response to perturbations. On figure 2, one can see that the injured leg of athletes with ACLR show relatively high medial co-contraction levels, independent of task difficulty (e.g. both during

perturbed and unperturbed trials) while uninjured controls only increase medial co-contraction during perturbed tasks. This raises the question whether the high co-contraction in the injured leg of athletes with ACLR might be an overcompensation for the altered afferent input. Normally, if the ACL is intact, ACL loading results in excitation of the mechanoreceptors, which in turn sends afferent information to the CNS to increase hamstrings activation and inhibit quadriceps activation to avoid further ACL loading[25]. After ACL injury, athletes might compensate for the loss of proprioceptive information, by using a general pattern of increased co-contraction, in all situations independently of ACL loading[26].

Influence of cognitive loading

Additional cognitive loading had a larger influence on neuromuscular control (e.g. a larger reduction in HM activation and (medial) co-contraction) of the injured leg of athletes with ACLR than in controls (figure 3). The fact that no between-leg differences were found, indicate that this is a bilateral phenomenon. The impact of cognitive loading on neuromuscular control might be explained by Kahneman's theory of limited capacity of attention[27] that states that the ability to carry out multiple tasks at the same time depends on the availability of cognitive resources. If cognitive demands of all combined tasks exceed the processing capacity, the quality of one or more tasks need to be sacrificed. The fact that the dual-task influenced neuromuscular control of athletes with ACLR both during unperturbed and perturbed conditions, but in controls only during perturbed conditions (figure 4), indicates that cognitive demands exceeded the cognitive capacity earlier in injured athletes. This suggests that athletes with ACLR might either have a lower cognitive processing capacity than control subjects and/or the neuromuscular response of the ACL group is cognitively more demanding. Both options are plausible based on existing literature. On the one hand, a prospective study of Swanik et al. found that athletes who sustained an ACL injury had already a lower neurocognitive function at baseline, supporting the idea that athletes with ACLR might have a lower cognitive processing capacity. On the other hand, the neuromuscular response of athletes with ACLR might require more attention than the neuromuscular response of uninjured athletes because of impaired proprioceptive input.

Kapreli et al.[10] found for example that ACL patients have an increased activation in brain areas related with the conscious planning of movement during a simple knee flexion-extension task. Similarly, studies investigating postural control in elderly have shown that when proprioceptive input is disturbed, more attention is needed for the cognitive regulation of postural control[28]. The increased cognitive demands for postural control in elderly are often put forward as the reason for increased fall risk during dual-tasking[29]. Similarly, in athletes with ACLR, a limitation of cognitive resources might bring athletes in the situation that they lack the ability to allocate sufficient attention to the dynamic stabilization of the knee, resulting in increased risk for re-injuries. In our study, we did not find a reduction in accuracy of the dual-task, indicating that the athletes with ACLR did not sacrifice the dual-task for neuromuscular control.

Important to mention is that adding cognitive loading, resulted in more similar co-contraction and HM activation levels between control subjects and athletes with ACLR (figure 3). The athletes with ACLR show a reduction of the HM activation and (medial) co-contraction during conditions with dual-task compared to conditions without dual-task. Based on this observation, one might speculate that dual-tasks could partially suppress AMR in athletes with ACLR. Future studies should assess this hypothesis by investigating the effect of cognitive loads and distraction on AMR.

Clinical implications

The findings of this study add to the existing evidence that proprioceptive and neurocognitive impairments may have an important underlying contribution to the neuromuscular deficits in athletes with ACLR. This implies that ACL rehabilitation and RTS testing should address the entire sensorimotor function [10,12]. Therefore, patients should be exposed to different environmental constraints during rehabilitation to explore and optimize their motor responses to the variety of constraints they might experience during sports situations[12].

Limitations

The environmental challenges in this study give a general representation of how neuromuscular control of athletes with ACLR may be influenced in challenging environments such as during match play. We chose to use a visuospatial task and platform perturbations, as both tasks are standardized and therefore easy to reproduce[13]. However, both tasks are not sports specific. Future studies should therefore develop more sport-specific tasks, for example reacting to an opponent, a dual-task that includes a ball etc., and this to improve external validity. A second limitation is that we did not calculate alterations in landing kinematics, kinetics and joint forces and therefore have to rely on other (modelling) studies assessing the influence of muscle activation on actual ACL strains and the anterior tibial translation mechanism. Third, both groups were not perfectly matched for age. The group of athletes with ACLR was significantly older (23.7 +/- 4.3 years) compared to the control group (21.4 +/- 1.5 years). Finally, we want to stress that this is an exploratory study without adjustment for multiple comparisons. This strategy avoids increasing the risk for false negatives (type II errors) which is desirable in explorative studies but one should be aware that this also has the disadvantage of increasing the risk for false positives (type I errors)[20,21]. Therefore, future studies need to confirm the findings.

CONCLUSION

Athletes with ACLR show higher hamstrings activation and lower VM activation in their injured leg, compared to uninjured controls, which might represent an arthrogenic muscle response (AMR). Furthermore, the injured leg of athletes with ACLR show less adaptation of medial co-contraction and VM, VL and GL activation levels in response to perturbations compared to uninjured athletes. This might be the result of loss of afferent information due to damage of mechanoreceptors in the ACL, potentially compensated by a general pattern of increased co-contraction in all situations independently of ACL loading. Furthermore, increased cognitive loading had a larger influence on the neuromuscular control of the injured leg athletes with ACLR, compared to uninjured controls, indicating that neurocognitive limitations may contribute to altered neuromuscular control in athletes

with ACLR. This study could not demonstrate clear between-leg differences in neuromuscular response to environmental challenges in ACLR athletes, indicating that the altered neuromuscular response might be a bilateral deficit. The findings of this study confirm the hypothesis that the injured leg of athletes with ACLR show a different neuromuscular response to environmental challenges compared to uninjured athletes, suggesting that athletes with ACLR are not yet fully prepared for environmental challenges at time of RTS.

Conflict of interest statement

Declarations of interest: none

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

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Figure 1. A) Illustration of stepping down-task. B) Example of the cognitive dual-task. The color of the frame and the meaning of the word are similar, thus the participant has to answer with the font color, namely 'red'.

Figure 2. Graphical illustration of the significant group x perturbation interaction effect found in vastus medialis (VM), vastus lateralis (VL) and gastrocnemius lateralis (GL) activation and medial co-contraction index (CCI). For the GL activation, also a leg x perturbation effect was found. The red line represents the average muscle activation and CCI in the injured leg of athletes with anterior cruciate ligament reconstruction (ACLR) during the unperturbed and perturbed tasks (red dotted line represents the uninjured leg of the athletes with ACLR). The black line represents the activation and CCI of the control group.

MVC=maximum voluntary contraction

Figure 3. Graphical illustration of the significant group x dual-task interaction effect found in hamstrings medialis (HM) activation, co-contraction index (CCI) and medial CCI. The red line represents the average muscle activation and CCI in the athletes with anterior cruciate ligament reconstruction (ACLR) during the tasks without and with dual-task. The black line represents the activation and CCI of the control group.

MVC=maximum voluntary contraction

Figure 4. Graphical illustration of the significant group x perturbation x dual-task interaction effect found in hamstrings medialis (HM) activation. The red line represents the average muscle activation in the injured leg of athletes with anterior cruciate ligament reconstruction (ACLR) during the unperturbed (left graph) and perturbed trials (right graph). The black line represents the HM activation of the control group.

MVC=maximum voluntary contraction

	ACL	Control	T-test
Participants (n)	20	20	
Height (cm)	179.1 ± 9.6	179.8 ± 9.7	p=0.816
Body weight (kilograms)	76.7 ± 11.5	71.5 ± 9.4	p=0.125
Age (years)	23.7 ± 4.3	21.4 ± 1.5	p=0.034
Gender	6 females /14 males	6 females/ 14 males	
Soccer	n=12	n=12	
Volleyball	n=4	n=4	
Basketball	n=2	n=2	
Hurdles	n=1	n=1	
Dancing	n=1	n=1	

Table 1: Participant characteristics (mean ± SD). n=number of participants; BW=body weight;

	ACL		Control	Mann Withney U-test
	Injured leg	Uninjured leg		
Accuracy dual task DUAL (%)	93 (71-100)	100 (86-100)	100 (82-100)	p=0.330 ¹ p=0.512 ² p=0.799 ³
Accuracy dual task PERTDUAL (%)	100 (96-100)	100 (96-100)	100 (99-100)	p=0.380 ¹ p=0.659 ² p=0.758 ³
Stability PERT (%)	69 (50-75)	75 (38-78)	69 (59-88)	p=0.589 ¹ p=0.883 ² p=0.862 ³
Stability PERTDUAL (%)	88 (75-100)	88 (86-100)	88 (75-100)	p=0.975 ¹ p=0.799 ² p=0.904 ³

Table 2. Accuracy (median, 1th quartile-3rd quartile) of the dual-task and proportion of successful responses to the perturbations (in %) for the injured and uninjured leg of the ACL group and the control group. Mann Whitney U-tests showed no significant differences between both legs of the ACL group (¹), the ACL injured leg and controls (²) and between the ACL uninjured legs and controls (³).

		NORMAL	DUAL	PERT	DUALPERT
VM	ACL injured	6.21 (5.12)	6.53 (5.06)	8.99 (7.06)	8.23 (6.81)
	ACL uninjured	7.99 (5.09)	8.53 (5.11)	12.25 (8.94)	11.77 (8.34)
	Control	9.05 (5.87)	10.25 (5.82)	16.96 (10.28)	15.07 (9.39)

VL	ACL injured	9.59 (5.12)	10.85 (5.06)	13.15 (7.06)	12.18 (6.81)
	ACL uninjured	11.05 (7.56)	12.11 (8.89)	13.73 (9.85)	14.24 (9.41)
	Control	11.52 (5.87)	14.27 (5.82)	16.74 (10.28)	18.05 (9.39)
HM	ACL injured	7.26 (4.22)	4.68 (2.53)	7.64 (3.73)	6.53 (3.46)
	ACL uninjured	5.87 (4.79)	3.78 (2.76)	8.05 (5.93)	7.21 (6.23)
	Control	3.41 (1.93)	3.90 (3.25)	6.41 (3.62)	6.03 (3.77)
HL	ACL injured	7.25 (4.87)	6.95 (4.79)	8.56 (4.12)	7.64 (3.15)
	ACL uninjured	3.16 (2.73)	2.65 (2.10)	4.35 (3.28)	3.72 (3.11)
	Control	2.42 (1.55)	2.97 (2.47)	3.93 (1.93)	3.57 (2.04)
GM	ACL injured	22.43 (13.90)	23.12 (15.85)	23.85 (14.14)	23.92 (14.60)
	ACL uninjured	19.54 (12.99)	22.12 (14.47)	30.74 (32.94)	31.16 (37.86)
	Control	32.29 (22.82)	31.91 (29.06)	44.79 (40.27)	42.23 (42.26)
GL	ACL injured	8.89 (6.26)	9.63 (8.56)	9.93 (6.78)	9.94 (6.77)
	ACL uninjured	11.57 (8.10)	11.11 (9.85)	14.05 (10.11)	14.66 (9.23)
	Control	12.56 (7.59)	11.55 (4.70)	15.93 (7.59)	15.44 (5.85)
Glut	ACL injured	15.50 (13.20)	18.56 (17.75)	18.73 (14.91)	15.91 (15.29)
	ACL uninjured	19.78 (13.61)	22.95 (17.50)	24.51 (18.50)	21.67 (18.62)
	Control	22.75(17.15)	27.44 (19.58)	27.22 (17.78)	27.88 (16.47)
CCI	ACL injured	31.20 (19.93)	21.68 (14.18)	29.62 (13.61)	23.51 (13.13)
	ACL uninjured	14.30 (13.16)	9.48 (7.63)	19.61 (16.42)	16.74 (16.83)
	Control	8.25 (4.57)	9.70 (9.32)	14.32 (8.10)	13.31 (8.69)
CCI med	ACL injured	13.83 (9.50)	9.09 (8.30)	14.92 (10.57)	12.39 (10.54)
	ACL uninjured	10.79 (11.36)	5.20 (4.41)	12.48 (10.93)	9.09 (8.47)
	Control	5.99 (4.59)	6.23 (5.95)	11.69 (9.72)	11.24 (10.69)
CCI lat	ACL injured	13.25 (10.62)	11.42 (7.67)	15.31 (8.61)	13.91 (9.58)
	ACL uninjured	5.52 (5.66)	4.14 (3.66)	7.88 (6.98)	6.60 (6.08)
	Control	3.26 (2.40)	4.01 (3.99)	5.19 (3.10)	4.58 (3.04)

Table 3. Mean IEMG (SD) of the different lower limb muscles and mean CCI's (SD) for the different groups (ACL injured leg, ACL uninjured leg and control group) during the 4 tasks (NORMAL, DUAL, PERT and DUALPERT).

SD=standard deviation; ACL = anterior cruciate ligament; NORMAL = Stepping-down task without environmental constraints, DUAL= Stepping-down task combined with dual task; PERT= Stepping-down task combined with unpredictable base of support perturbations; PERTDUAL = Stepping-down task combined with dual-task and unpredictable base of support perturbations