Cortical Motor Planning and Biomechanical Stability During Unplanned Jump-Landings in Males With ACL-Reconstruction

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Abstract

Context: Athletes with anterior cruciate ligament (ACL) reconstruction exhibit increased cortical motor planning during simple sensorimotor tasks compared to healthy controls. This may interfere with proper decision-making during time-constrained movements elevating the re-injury risk.

Objective: To compare cortical motor planning and biomechanical stability during jump-landings between participants with ACL-reconstruction and healthy individuals.

Design: Cross-sectional exploratory study.

Setting: Laboratory patients or other participants: Ten males with ACL-reconstruction (28±4 yrs., 63±35 months post-surgery) and 17 healthy males (28±4 yrs.) completed pre-planned (landing leg shown before take-off; n=43±4) and unplanned (visual cue during flight; n=51±5) countermovement-jumps with single-leg-landings.

Main outcome measures: Movement-related cortical potentials (MRCP) and frontal theta frequency power before the jump were analyzed using electroencephalography. MRCP were subdivided into three successive 0.5 sec epochs (readiness potential 1 and 2; RP and negative slope; NS) relative to movement onset (higher values indicative of more motor planning). Theta power was calculated for the last 0.5 sec prior to movement onset (higher values indicative of more focused attention). Biomechanical landing stability was measured via vertical peak ground reaction force, time to stabilization, and center of pressure.

Results: Both conditions evoked MRCP at all epochs in both groups. During the unplanned condition, the ACL-reconstructed group exhibited slightly, but not significantly higher MRCP (RP-1:p=0.651, d=0.44, RP-2:p=0.451, d=0.48; NS:p=0.482, d=0.41). The ACL-reconstructed group also showed slightly higher theta power values during the pre-planned (p=0.175, d=0.5) and unplanned condition (p=0.422, d=0.3) reaching small to moderate effect sizes. In none of the biomechanical outcomes, both groups differed significantly (p>0.05). No significant condition and group interactions occurred (p>0.05).
Conclusions: Our jump-landing task evoked MRCP. Although not significant between groups, the observed effect sizes provide first indication that males with ACL-reconstruction may persistently rely on more cortical motor planning associated with unplanned jump-landings. Confirmatory studies with larger sample sizes are warranted.

Trial registry: clinicalTrials.gov (NCT03336060).

Keywords: Neurocognition, decision-making, EEG, Anticipation, Agility, ACL rehabilitation
Introduction

The majority of anterior cruciate ligament (ACL) tears in team sports, such as football or basketball occur in non-contact situations. The surgical reconstruction of the ACL represents a standard procedure aiming to correct the biomechanical function of the ligament in athletes. Afferent nerve fibers connect the ACL with the posterior articular branches of the tibial nerve. Located near the femoral attachment of the ACL, the mechanoreceptors of the nerve fibers inform the brain (somatosensory cortex) regarding joint proprioception and movement through ascending pathways. The rupture and reconstruction of the torn ligament lead to considerable loss or damage of ACL mechanoreceptors. Despite the replacement of the native ACL by a tendon graft, neurosensory deficits persist as there are doubts that any significant re-innervation occurs. With deficient ACL afferent, proprioceptive, and other somatosensory input, the brain is less able to fine-tune movement and mediate joint stability through descending neuromuscular pathways. Neurophysiological evidence suggests that ACL rupture and resulting sensory deafferentation are associated with persistent changes of functional brain activation patterns during movement. These neural adaptations may contribute to the frequently observed impairments of motor functions (e.g., altered proprioception, postural control, muscle strength and landing mechanics) and high re-injury rates after return to sports in affected individuals.

Specifically, studies using electroencephalography (EEG) have shown that individuals with ACL-reconstruction exhibit an enhanced activity of the frontal and/or parietal cortex during both passive knee loading via arthrometry and active execution of sensorimotor tasks, such as angle and force reproduction. Results from magnetic resonance imaging studies support this, where ACL-injured individuals demonstrate higher activation in areas of the brain responsible for motor planning, sensory processing and visual control during isolated knee flexion-extension movements compared to healthy controls. Thus, the brain of ACL-injured/-reconstructed individuals seems to rely more on higher-order attentional control and soma-
tosensory processing to compensate for the neuromechanical decoupling and to maintain task performance. Besides these central nervous compensation strategies, transcranial magnetic stimulation studies report long-lasting changes of the motor cortex. Specifically, ACL reconstructed patients exhibit a decreased corticomotor excitability of areas responsible for the innervation of the knee muscles.

However, the rather simple and feedback-controlled movement tasks have low ecological validity as they do not fully reflect the cognitive-motor demands of complex playing situations.

In team sports, athletes interact in a highly variable and unpredictable environment. They need to process a multitude of visual stimuli while simultaneously monitoring and adjusting their own motor plans and actions spontaneously to sudden changes. Previous research has attempted to mimic the time-constrained decision-making demands in athletic movements by using unplanned tasks. During these tasks, a stimulus indicating the requested landing leg or side-cutting direction after a run or jump was displayed only shortly before ground contact. Compared to a pre-planned control condition, where this information was already known before the beginning of the trial, the unplanned task induced altered landing biomechanics, suggestive of a higher risk for non-contact ACL-injury. Beyond this, the unplanned condition predisposes erroneous decision-making (e.g., landing on the wrong side).

However, the cortical processes associated with such sports-related movements are still unclear. One may speculate that participants with ACL-reconstruction need more brain resources to prepare and initiate unplanned movements compared to healthy individuals (no history of severe musculoskeletal injuries requiring surgical repair). This may interfere with proper decision-making during unplanned movements resulting in different knee mechanics and an elevated re-injury risk. The EEG can provide markers of underlying neurophysiologic mechanisms with high time resolution. Movement-related cortical potentials (MRCP) and frontal theta frequency power are valid measures to quantify motor planning and attentional
processes associated with voluntary movements like a jump.\textsuperscript{21,22} This study aimed to compare cortical motor planning, biomechanical landing stability, and decision-making quality in pre-planned and unplanned jump-landings between participants with ACL-reconstruction and healthy (control) individuals.

**Methods**

**Study design**

The cross-sectional exploratory study was performed according to the Guidelines for Good Clinical Practice laid down in the Declaration of Helsinki. Approval was obtained by the local ethics committee (reference number: 2017/27). Each participant provided written informed consent before study inclusion. The study was registered at clinicalTrials.gov (NCT03336060). The control group was obtained from an earlier trial.\textsuperscript{20} All participants received a one-time expense allowance of 50 Euro.

**Sample**

Participants were recruited at local physical rehabilitation centers, physiotherapy and medical practices, sports clubs, fitness centers, and the local university campus using flyers, e-mails and word of mouth. Inclusion criteria for participants with ACL-reconstruction and healthy participants were: (1) male sex, (2) age between 20 and 40 years, (3) regular sporting activity (\( \geq 2 \) times per week), (4) counter-movement jump (CMJ) height of \( \geq 30 \) cm to ensure sufficient decision-making time during the jump. Additionally, ACL-reconstructed participants were included, if they (5) had a history of unilateral, non-contact ACL injury with reconstruction surgery (\( > 1 \) year), irrespective of the graft used and surgical procedure, (6) reached a limb symmetry index in the single-leg hop for distance test of \( > 85 \) percent and (7) were cleared for return to sport in a shared decision process). Exclusion criteria for ACL-reconstructed and healthy participants encompassed (1) severe somatic and/or psychological diseases/disorders, (2) acute or chronic joint/tissue inflammation, (3) intake of drugs modify-
ing pain perception and proprioception, (4) muscle soreness, as well as (5) a history of brain and head injuries (< 1 year). Additional exclusion criteria for the participants with ACL-reconstruction were (6) exorbitant concomitant knee injury (i.e., bone bruise grade 3 or 4, full-thickness articular cartilage lesion larger than 1 cm² and ‘unhappy triad’) as well as (7) a previous ACL injury or surgery of the uninvolved knee. Healthy control participants with a history of severe musculoskeletal injuries (e.g., ACL-tear) or surgery of the lower limb were excluded.

We only included male participants in this study to avoid potential confounding effects of sex on study outcomes. Females have been shown to exhibit altered landing mechanics and are at higher risk of sustaining a knee injury. As a result, ACL-injury mechanisms have been primarily explored in female athletes, and it is also important to consider any male-specific injury risk factors. Furthermore, it was easier for males to achieve the required jump height of about 30 cm in the countermovement jump (see jump-landing task below).

The sample size was determined using means and standard deviations reported in a previous EEG study comparing the mean frontal theta frequency power during a sensorimotor task between ACL-reconstructed and healthy participants. The a priori sample size calculation (two-tailed α = 0.05, β = 0.2; G*Power, Version: 3.1.9.2, University of Düsseldorf) resulted in a minimum of 10 participants for each group.

**Experimental setup**

All individuals visited the university laboratory on two days within one week (≥ 3 days in between the two days) at a comparable time of day. During visit 1, we familiarized the participants with the jump-landing task. During the familiarization session, we asked each participant to rate their level of fear of (re-)injury under the unplanned condition. Furthermore, data regarding anthropometrics, physical activity, neuromuscular performance, and self-reported knee function were assessed from all participants. For all participants with ACL-reconstruction, we documented the time since surgery. Visit 2 consisted of the actual meas-
urements (jump-landing task). Data collection was performed under standardized circum-
stances (room size, temperature, humidity, workplace, and lighting).

**Jump-landing-task**

All participants performed repeated counter-movement jumps with planned vs. unplanned single-leg landings on a pressure plate.

For both landing conditions, the participants were required to produce flight times of about 500 msec (corresponding to a jump height of about 30 cm) resulting in available response times of approximately 380 msec during the jump in the unplanned condition, which is in line with previous work. All participants practiced generating these flight times during the familiarization session (day 1).

In the pre-planned condition, the participants received the visual cue depicting the requested landing leg (left or right footprint displayed on a presentation slide; Microsoft PowerPoint 2010; on a 17-inch laptop screen, 2.5 m in front of the participants) prior to the jump. In the unplanned condition, this information was shown only upon take-off (120 msec delay after leaving the ground).

For both conditions, at least 40 valid trials were performed for analysis. To avoid exhaustion, the jumps were divided into 6 to 7 blocks, depending on the success rate of landings, of 14 jumps with 5-minute rests in a seated position in between. As the rate of successful landings was higher during the preplanned trials, the preplanned to unplanned randomization ratio was 1:1 until the needed number of preplanned landings was reached. After that point, the randomization ratio was changed to 1:2. The landing side of both conditions was equally distributed. Randomization was performed using BIAS for windows (University Frankfurt, Germany, V.11.06).

The participants were instructed before each jump to stand in a hip-width position (knee slightly flexed and hands at the hip). Then, the participants were verbally informed about the upcoming landing condition according to the randomization list. At this moment, we asked
the participants to mentally prepare themselves for the upcoming jump landing for at least 3
seconds (measured using a stopwatch, which was not seen by the participants) before initiat-
ing the movement on their own. We used this period to guarantee a sufficient pre-movement
planning time. After landing, participants were asked to stabilize as soon as possible and
maintain a stable stance for 10 seconds while focusing a fixation cross mounted to the wall at
eye level. Further details regarding the setup of the jump-landing-task are described else-
where. 

EEG set-up and MRCP and frontal theta frequency power acquisition (primary outcome)
The cortical activity before the jumps was measured using a 32-channel EEG system (sample
rate: 500 Hz, 24-bit analogue-to-digital) with a wireless amplifier (LiveAmp, BrainProducts,
Gilching, Germany). An integrated three-axis acceleration sensor (measurement range: ± 2 g,
resolution: 1 mg/bit, 12 bit; error: ± 200 g) carried in a custom-made backpack (total weight:
700 g) was attached to the upper back of the participants. The active slim electrodes were em-
bedded in the EEG cap (actiCAP, Easycap, Herrsching, Germany) according to the 10–20
international system. Impedance was kept below 5 kΩ and no online filters were applied. We
used the FCz electrode as reference. The EEG was continuously recorded throughout the
whole jump-landing task. EEG data were filtered with a Butterworth high-pass filter of
0.001 Hz (24 dB/octave) and a Butterworth low-pass filter of 40 Hz (24 dB/octave). For each
trial, we segmented the EEG signals into epochs of 2500 msec, from 2000 msec before to 500
msec after movement onset (jump).
For movement onset detection, we used the acceleration data, which was time synchronized
with the EEG data recording. We calculated the first derivative of the vertical accelerations
(y-axis) associated with the initiation of the jump using the Formula Evaluator (level trigger
threshold: -7 µV). If this threshold was not appropriate, the onset time was manually adjusted
to the time, where the vertical acceleration exceeded the average of the previous level by two
standard deviations. Trials were eliminated from analyses if the movement onset was not
clearly detectable (e.g., very slow movement or cancelation of an initiated movement) and/or the standing time before the initiation of the jump was too short (< 3 sec).

The MRCP is a low-frequency slowly increasing negative potential, which begins about two seconds before voluntary movements. The MRCP is known to represent the cortical processes associated with the planning and preparation of movements, such as a jump. A higher negativity indicates a greater neurocognitive involvement associated with the movement planning and preparation and vice versa. According to Spring et al., the MRCP can be divided chronologically into the following periods relative to movement initiation (0 msec):

- readiness potential one (RP-1: −1500 msec to −1000 msec)
- readiness potential two (RP-2: −1000 msec to −500 msec)
- negative slope (NS: −500 msec to 0 msec; Fig. 1)

The non-lateralized readiness potentials reflect the rather unconscious movement-related decision-making processes of the pre- and supplementary motor cortex. The steeper negative slope potential corresponds to the conscious movement preparation processes of side-specific body movements and occurs in the contralateral primary motor cortex. The mean activity of the MRCP was calculated for the fronto-central (FC1 and FC2) and central electrodes (C3, CZ, and C4) as these channels are located above the supplementary and primary motor areas. To examine if our jump-landing task evoked a MRCP, the mean values and the 95% confidence intervals of the pre-planned and unplanned condition were calculated for the above-mentioned electrodes at each time epoch, regardless of group belonging. The criteria for MRCP were fulfilled if the level of negativity reached statistical significance (based on the 95% confidence interval). Only these electrodes were considered for further analyses. For all participants, the mean of the MRCP was calculated for successful trials, separately for both limbs and conditions.

For frequency domain-specific analyses within the theta power spectrum (4 to 7 Hz) fast Fourier transformation was used. The theta frequency power is most prominent over the midline fronto-central electrodes. It is generated in the anterior cingulate cortex, which is thought to be part of the human executive attentional system. Higher frontal theta activity is related to a
higher level of focused attention. Previous work demonstrated its sensitivity for the atten-
tional demands associated with the motor planning of athletic movements, such as pre-
planned jump and sidestepping maneuvers. According to Burcal et al. the frontal theta
frequency power was calculated for the last 0.5 sec before movement onset and averaged for
the successful trials of both conditions. The variable was analyzed for the frontal midline (FZ)
electrode.
To reduce EEG artefacts generated by body and eye movements, the participants were in-
structed before each jump to stand in a quiet and relaxed position, while visually fixating a
cross on a screen in front of them (to minimize horizontal eye movements and eye blinks).
This position had to be maintained until the visual inspection of the EEG channels indicated
clean data recording and impedance lower than 5 kΩ.
To remove non-stereotypical artefacts (e.g., low frequency drifts and offsets due to move-
ment, sweating, horizontal eye movements, etc.), we conducted an individual-based semi-
automatic independent component analysis (ICA) by filtering the data with a higher cut-off
for the high pass frequency (1 Hz). The resulting ICA matrix (with excluded non-stereotypical
artefact components) was then applied to the original non-high-pass filtered (0.001 Hz) data.
This approach (for details, please refer to Winkler et al.) enabled us to clearly identify eye
blinks, which we manually removed using ocular correction ICA (FP2 electrode vs. common
reference). Furthermore, we conducted an automated-artefact rejection to remove potentially
remaining artefacts according to the criteria used by Saliasi et al. Based on a final visual
inspection, only artefact-free trials were used for analysis.
Biomechanical stability and decision-making quality (secondary outcome)
A capacitive pressure measurement platform (Zebris FDM, Zebris Medical GmbH, Isny,
Germany; 50 Hz, error of measurement: ≤ 5%) was used to assess the biomechanical landing
stability of successful trials for both limbs and landing conditions. Trials were considered
successful, if the landing was performed on the correct side and the stable single-leg stance
was maintained without touching the ground with the free leg, leaving the force plate or touching the ground with the hands for at least 10 seconds. We measured three biomechanical parameters: peak vertical ground reaction force (pVGRF) at landing and center of pressure (CoP) path length (first 2.5 sec upon landing) as well as time to stabilization (TTS; estimated relative to the whole standing period of 10 sec. after landing). Additionally, we collected the number of standing errors (i.e., landing on the correct leg but touching the pressure plate with the free leg/hands or leaving the platform; SE). As a measure of decision-making quality, the number of decision errors (i.e., landing with wrong or both feet) was documented. For more details of these outcomes, please refer to a previous trial.

To examine the comparability between both groups, the following additional variables were assessed during visit 1 from all participants: Anthropometrics (body weight and height and BMI), physical activity (MET/h) during the last week using the IPAQ short form and the number of participants who were engaged in team game sports at least once a week. Neuro-muscular function was operationalized by the maximum counter-movement jump height (with hands at hip; highest jump out of three) and single-leg hop for distance limb symmetry index (the longest distanced jump per limb out of three). Self-reported knee function of the ACL-reconstructed knee and reconstructed knee and those of healthy participants were measured using the Lysholm Knee Score Scale. Task-specific fear of movement/reinjury during the unplanned condition was assessed during the familiarization session using a 10 cm visual analog scale (0 cm = very low, 10 cm = very high pronounced). Self-reported level of alertness, as well as fatigue of the lower limb (before, in the middle and after the jump-landing task; mean of all three time points), were assessed during the actual jump-landing task at visit 2 using the same 10 cm visual analog scale. We assessed such self-reported outcomes as they may influence both, pre-movement cortical activity as well as biomechanical landing stability. Finally, we assessed the flight time of each jump-landing trial, because this variable corre-
sponds to the available response time during the jump. Shorter flight times are associated with a lower decision-making quality during the unplanned condition.\textsuperscript{20}

Statistics

All analyses were conducted after examining the underlying assumptions for parametric/non-parametric testing. Descriptive reporting included means or medians plus standard deviations and 95\% confidence intervals.

Within groups, the cortical correlates of motor planning were compared 1) between the preplanned and unplanned condition using dependent t-Tests or Wilcoxon signed rank test and 2) between groups (within conditions) using independent t-Tests or Mann-Whitney-U-Tests. To test for potential significant condition x group interaction effects the between condition differences were compared between groups again using independent t-Tests or Mann-Whitney-U-Tests. The same procedure was used for the biomechanical outcomes. Regarding the standing and decision errors, the relative error count in percent was calculated. Here, within and between group analyses were conducted by applying non-parametric statistical tests.

To investigate the potential effects of limb on both the cortical activity and biomechanical outcomes of both conditions within the ACL-reconstructed group, we compared the individual variables between the operated and the unaffected limb. Between groups, we tested the differences between the ACL-reconstructed and the dominant healthy control limb for significance. If significant side differences occurred within or between groups, we adopted the above-mentioned analyses by matching the ACL-reconstructed with the dominant limb of the healthy participants and vice versa. If no significant differences occurred, we performed the statistical analyses based on the average values of both limbs together for each group. As a supplement to significance testing using the p-value, we calculated effect sizes (Cohen d; small: d = 0.2; medium: d = 0.5; large effects: d = 0.8)\textsuperscript{34} to estimate and interpret the within and between condition differences regardless of sample size.\textsuperscript{35} Furthermore, we calculated the
post hoc beta power ($\beta$) for the MRCP comparisons within and between both groups. Due to the small sample size, we conducted no cofactor analyses.

The alpha error was set at 5%. All statistical analyses were performed using SPSS (IBM SPSS Statistics 24, Chicago, IL, USA) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, Washington, USA). Cohen $d$ effect sizes and $\beta$ power were both calculated with G*Power (Version 3.1.9.2; University of Düsseldorf). All EEG data processing was applied using the BrainVision Analyzer software (Brain Products, Gilching, Germany).

**Results**

Ten participants with ACL-reconstruction and 17 healthy individuals completed the jump-landing task, no one withdrew consent, and no one was excluded. In terms of the assessed participant characterizing variables (Tab. 1), no significant differences between both groups were found apart from self-reported knee function, which was lower in the participants with ACL-reconstruction compared to the healthy participants ($p > 0.05$). In both groups, the unplanned condition resulted in significantly longer flight times compared to the pre-planned condition ($p < 0.05$). However, the flight times of both conditions were not significantly different between groups ($p > 0.05$; Tab. 1).

In both conditions, the cortical and biomechanical measures did not differ significantly between the ACL-reconstructed and unaffected limb ($p > 0.05$). The differences between the ACL-reconstructed and the dominant limb of the healthy participants were also not significant ($p > 0.05$).

Both groups performed a comparable total number of pre-planned (ACL-reconstruction: $n = 43 \pm 4$; healthy participants: $42 \pm 3$) and unplanned (ACL-reconstruction: $n = 50 \pm 7$; healthy participants: $51 \pm 5$) jump-landings. The number of successful trials for both the pre-planned (ACL-reconstruction: $n = 43 \pm 4$; healthy participants: $42 \pm 3$) and unplanned condition (ACL-reconstruction: $n = 36 \pm 6$; healthy participants: $37 \pm 4$) was also similar in both groups.
Because of movement-related artefacts, not all of these trials could be used for the analyses of the cortical correlates of motor planning (pre-planned: ACL-reconstruction: n = 35 ± 8; healthy participants: n = 35 ± 5 included; unplanned: ACL-reconstruction: n = 29 ± 9; healthy participants: 32 ± 6 included). The corresponding trials were also removed from the biomechanical analysis.

Cortical correlates of motor planning

Both the pre-planned and unplanned conditions evoked a MRCP at all epochs regardless of group (Fig. 1). The cortical potential was detected at the central midline (CZ) electrode only (Fig. 2).

Compared to the pre-planned condition, the unplanned task did result in slightly but not significantly higher MRCP within the participants with ACL-reconstruction (RP-1: +28%, p > 0.05; RP-2: +81%, p > 0.05; NS: +38%; p > 0.05; Tab. 2) and similar values for the healthy participants (RP-1: -11%, p > 0.05; RP-2: -18%, p > 0.05; NS: -15%, p > 0.05; Tab. 2). Between groups comparison indicated slightly higher values of the participants with ACL-reconstruction compared to the healthy participants during the unplanned condition, which again lacked statistical significance (UN: RP-1: +269%, p > 0.05; RP-2: +101%, p > 0.05; NS: +53%, p > 0.05; Tab. 2). During the pre-planned condition, both groups produced similar, not significantly different MRCP (p > 0.05; Tab. 2). No significant condition x group interaction effects occurred (RP1: p = 0.684, d = 0.14, RP2: p = 0.21, d = 0.44, NS: p = 0.378, d = 0.41).

In terms of frontal theta frequency power, within both groups, no significantly different values were found between both conditions (p > 0.05). The ACL-reconstructed group did again produced slightly but not significantly higher values compared to the healthy participants (pre-planned +20%; $Z_{(1,25)} = 1.4$, p = 0.175, d = 0.54, β = 25%; unplanned: +8%; $Z_{(1)} = 0.8$, p = 0.422, d = 0.31, β = 11 %). No significant condition x group interaction effects occurred (p = 0.359).
Biomechanical landing stability and decision-making quality

In both groups, the unplanned condition resulted in higher CoPs (ACL-reconstruction: 19%, $t_{(9)} = 3.5$, $p = 0.007$, $d = 1.1$; healthy participants: +12%, $t_{(16)} = 3.9$, $p < 0.01$, $d = 1.0$) and more standing errors, reaching high effect sizes (ACL-reconstruction: +5%, $Z_{(9)} = -2.4$, $p = 0.017$, $d = 0.7$; healthy participants: +4%, $Z_{(16)} = -3.2$, $p = 0.001$, $d = 1.0$). However, between groups, both variables did not differ significantly neither within nor between both conditions ($p > 0.05$). Within groups, no between condition differences were found in terms of TTS (ACL-reconstruction: $t_{(9)} = -1.7$, $p = 0.12$, $d = -0.5$; healthy participants: $t_{(16)} = -1.5$, $p = 0.015$, $d = -0.3$) and pVGRF (ACL-reconstruction: $t_{(9)} = 1.3$, $p = 0.22$, $d = 0.4$; healthy participants: $t_{(16)} = 0.94$, $p = 0.36$, $d = 0.2$). Between groups, both variables did not differ significantly neither within nor between both conditions ($p > 0.05$).

With regard to decision-making quality, both groups produced significantly more decision errors during the unplanned compared to the pre-planned condition (ACL-reconstruction: +22%, $Z_{(9)} = -2.8$, $p = 0.005$; healthy participants: +19%, $Z_{(16)} = -3.5$, $p < 0.001$). The number of decision errors was not significantly different between groups ($p > 0.05$).

**Discussion**

The present study is the first to investigate the cortical motor planning processes associated with unplanned athletic movements in individuals with ACL-reconstruction. Our jump-landing task evoked a MRCP irrespective of group and landing condition. Contrasting our assumption, the brain of participants with ACL-reconstruction did not rely on a significantly higher level of cortical motor planning and attention to initiate unplanned movements compared to the healthy participants. Both groups did not significantly differ in terms of the assessed biomechanical landing stability and decision-making quality measures and were similar across all characteristics except self-reported knee function.

Cortical correlates of motor planning
Our finding of non-significant different cortical activities between the participants with ACL-reconstruction and the healthy participants contrasts with previous evidence at the first glance. Authors of EEG and fMRI studies found ACL-reconstructed/-injured individuals to exhibit changes in functional brain activation patterns during sensorimotor tasks, such as joint repositioning and knee flexion/extension movements. According to the neuroplasticity hypothesis, these neural changes (e.g., increased motor planning and focused attention) have been interpreted as adaptation strategies of the central nervous system to compensate for the trauma-induced sensory deafferentation aiming to maintain motor tasks performance. Contrary to these studies, we assessed the cortical activity before movement initiation and not during motor executions. Compared to the latter, standing in a stable position during the motor preparation period does not rely on excessive sensory input from the knee joint.

However, although not statistically significant, the participants with ACL-reconstruction still tended to exhibit slightly (small to moderate effect sizes) higher MRCP during the unplanned task than the healthy participants did. This occurred throughout all three time epochs. Therefore, it seems that the brain of individuals with ACL-reconstruction may potentially require more activity for both the unconscious (pre- and supplementary motor cortex; RP-1, RP-2) and the conscious motor planning (primary motor cortex; NS) associated with the jump.

This trend may be partially explained by persistent reductions in corticomotor excitability that has been demonstrated in individuals with ACL-reconstruction. This would suggest that those individuals require greater stimulus to excite the descending cortical pathways (i.e., higher motor threshold) for innervating the knee muscles and initiating the movement. Another explanation for the higher MRCP of the ACL-reconstructed group may refer to the perceived task demands by the participants. In unplanned landings, the knee is exposed to higher loads, as there is not sufficient time for feed-forward planning of the landing. Participants with ACL-reconstruction may have perceived it more challenging to perform the unplanned task possibly due to lower confidence to load the operated knee because its function may not
have been completely restored yet as indicated by a significantly lower Lysholm score. Possibly, this has led to an increase of the motor thresholds as a higher level of internal resistance has to be overcome. This interpretation basically complies with the findings of a previous EEG study indicating that the initiation of a challenging movement like a bungee jump results in significantly higher MRCP compared to rather easy and safe movements (e.g., finger movements), because the latter makes less effort to overcome oneself to start moving.\textsuperscript{36} MRCP associated with our task occurred at the central midline (CZ) electrode only, regardless of condition, epoch, or group. This potential reflects the conscious intention to move and it occurs in the primary motor cortex contralateral to the moved body side.\textsuperscript{21} Due to the somatotopic organization of the cortex, we initially included the lateral electrodes C4 and C3, but due to lower extremities representation close to the midline,\textsuperscript{32} we did not find a laterality effect. The ACL-reconstructed group tended to exhibit higher pre-movement frontal theta frequency power values (small to medium effect sizes) compared to the healthy participants. This indicates that the affected individuals seem to direct more attentional resources to the jump. Possibly it is physically more demanding for those to achieve the required jump height throughout the jump-landing task as postoperative strength and self-reported knee function deficits may still persist. Nevertheless, the within and between group comparison lacked statistical significance. This is possibly attributed to the small sample size (e.g., low post hoc beta power) and large heterogeneity. The participants with ACL-reconstruction varied in time since surgery (28 to 140 months) and self-reported knee function (76 to 100 %) which may contribute to non-significant findings. On the other hand, the two groups were comparable across a range of characteristic variables which may make it more difficult to detect small effects or differences between both groups in terms of cortical activity. Higher-powered confirmatory studies are warranted to achieve statistical significance. Another potential reason for the non-significant differences in cortical activity may be that both groups performed the jump-landing task very
similarly in terms of jump height, decision-making quality and biomechanical landing stability. Future work including an ACL-reconstructed group with more neuromuscular impairments may result in different cortical activities.

Biomechanical landing stability and decision-making quality

The observed biomechanical landing safety and decision-making quality decrements during the unplanned compared to the pre-planned condition are in line with previous work.19,20 These task performance decrements are most likely the result of the time constraints making it difficult to prepare the landing properly during the jump.19 We did not find the ACL-reconstructed group to produce significantly greater performance decrements in terms of biomechanical landing safety and decision making quality compared to the healthy participants. This is not in line with previous findings indicating different landing mechanics in participants with ACL-reconstruction associated with potentially higher knee loading during both pre-planned38,39 and unplanned movements40. Besides insufficient statistical power, the non-significant between-group differences may be the result of the relatively long postoperative timeframe and the high level of neuromuscular restoration of the included participants. This may also explain, why we did not observe significant differences between the ACL-reconstructed and uninjured limb in any of the assessed outcomes. Niederer et al.41 found unplanned biomechanical jump-landing deficits of the ACL-reconstructed limb to persist up to 18 to 26 months after surgery. This period fits the proposed high risk for a subsequent ACL injury time after ACL-reconstruction and return to sports. Future studies should therefore replicate our approach considering this critical postoperative period.

Limitations

First, the statistical power of this exploratory study was too low to detect significant between-group differences. Second, because of the small sample size, we did not account for potential confounders, such as jump height, self-reported knee function, level of expertise or type of sport (open vs. closed skill sports)18 that may have affected task performance. For example,
one may speculate that open skill athletes (e.g., football, basketball), who interact in highly variable and unpredictable environments are more used to the demands associated with the unplanned condition compared to closed skill athletes (e.g., running) interacting in more consistent, predictable and self-paced environments. Third, the findings refer to male individuals only, who were capable to reach a minimum height of 30 cm in the countermovement jump.

Fourth, although we asked the participants to respond to the visual cue upon take-off, we cannot exclude that some may have still tended to guess the landing side or to follow their pre-defined motor plans regardless of the presented stimuli. Fifth, relative to the pre-planned condition, the unplanned task resulted in more unsuccessful trials. Therefore, a higher total number of unplanned trials were necessary to reach the pre-defined minimum number of successful trials for both conditions. Hence, participants with a higher landing/standing error rate were required to complete a larger number of trials, which may have predisposed fatigue or learning effects in single cases. Finally, due to excessive movement artefacts associated with the jump, the analysis of the cortical activity during the jump was not possible. In terms of the injury mechanism, this phase is even more critical as landing-related decision-making and movement adaptations in response to external stimuli may rely on substantial sensorimotor processing of the brain. Against this, our study should encourage scientists to investigate these neurocognitive processes during challenging athletic tasks, such as unplanned jump-landings by using Mobile Brain/Body Imaging methods.\textsuperscript{42}

Practical implications/ clinical take-home messages:

- Although not statistically significant, the present exploratory study provides first indications that return to sports cleared males with ACL-reconstruction may still tend to need more cortical motor planning associated with unplanned jump-landings.
- Future confirmatory studies with higher sample sizes, shorter postoperative timeframes and the inclusion of both females and males are warranted to verify this and to elucidate its potential implications for secondary injury prevention and return to sports.
- Unplanned jump-landings resulted in lower biomechanical landing stability and predisposed erroneous landing-related decision-making in both groups. Time-constrained decision-making is paramount for performance and injury prevention in open-skill sports. Coaches and sports medicine clinicians may consider implementing our or similar jump-landing tasks to screen and train their athletes.

**Conclusion**

Our jump-landing task evoked an MRCP irrespective of the group and landing condition. Although not statistically significant between groups, the observed small and medium sized effects may provide first indications that return to sports cleared males with ACL-reconstruction potentially rely on more cortical motor planning associated with unplanned jump landings. Confirmatory studies with larger sample sizes and shorter postoperative timeframes are highly warranted to corroborate these initial hints and to elucidate their potential implications for secondary injury prevention and return to sports.
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Author contribution statement: FG, JW, TE, and DN designed the jump-landing task. SV and TE supported FG in the development of the EEG setup. FG collected the data and carried out all calculations and statistical analyses. SV made a major contribution to the analyses of the EEG data. All authors discussed the results. FG wrote the first draft of the manuscript with support from SV. WB supervised the project. All authors revised the manuscript critically and agreed with the content of the submitted manuscript.
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Tab. 1. Characteristics of both groups

|                          | Controls (n=17) | ACLR-group (n=10) | p-value |
|--------------------------|----------------|-------------------|---------|
|                          | Mean ± SD (min - max.) | Mean ± SD (min - max.) |         |
| Age (years)              | 28 ± 4 (22 – 38) | 28 ± 4 (20 – 32)  | 0.96    |
| Height (cm)              | 182 ± 6 (171 – 194) | 183 ± 3 (178 – 188) | 0.85    |
| Weight (kg)              | 82 ± 11 (63 – 106) | 87 ± 8 (78 – 101)  | 0.21    |
| Time since surgery (month) | -              | 63 ± 35 (28 – 140) | -       |
| Physical activity (MET/h) | 70 ± 47 (23 – 175) | 63 ± 54 (4 – 172)  | 0.73    |
| Team game sports (min. 1x per week) ** | 6/15 (40 %) | 4/8 (50 %) | 0.69    |
| Explosive strength lower limb (CMJ-height; cm) | 40 ± 6 (30 – 51) | 36 ± 5 (30 – 45) | 0.12    |
| Limb symmetry SLHD (%)   | 96 ± 3 (1-11) | 96 ± 4 (1 – 12)   | 0.88    |
| Lysholm knee function score ** | 98 ± 3 (90-100) | 89 ± 8 (76 – 100) | 0.01    |
| Fear of (re-)injury (unplanned; VAS) ** | 2 ± 2 (0-8) | 2 ± 2 (0-7) | 0.96    |
| Self-reported level of attention (VAS) | 8 ± 1 (5 – 10) | 7 ± 2.4 (3 - 10) | 0.19    |
| Self-reported level of fatigue (VAS) | 3 ± 3 (0 – 7) | 5 ± 3 (1 - 8) | 0.33    |
| Flight time (planned vs. unplanned) | 472 ± 23 (411 – 499) vs. 483 ± 27 (414 – 515)* | 457 ± 28 (412 – 496) vs. 469 ± 29 (421 – 50 7)* | 0.76    |

MET = Metabolic Equivalents, CMJ = counter movement jump, SLHD = single leg hop for distance, VAS = visual analog scale, SD = standard deviation, ACLR = anterior cruciate ligament reconstructed, * p < 0.05, ** non-normally distributed data.
Tab. 2. Inference statistic results of within and between group comparisons for Movement-related-cortical potentials at the Cz-electrode

| Within groups | ACLR (pre-planned vs. unplanned) | Healthy (pre-planned vs. unplanned) |
|---------------|----------------------------------|-------------------------------------|
| **RP-1**      | \( T_{(9)} = 0.3, \ p = 0.783, \ d = 0.14, \ \beta = 7\% \) | \( T_{(16)} = -0.2, \ p = 0.827, \ d = 0.04, \ \beta = 5\% \) |
| **RP-2**      | \( T_{(9)} = 0.8, \ p = 0.444, \ d = 0.37, \ \beta = 19\% \) | \( T_{(16)} = -1.1, \ p = 0.294, \ d = 0.23, \ \beta = 14\% \) |
| **NS**        | \( T_{(9)} = 0.7, \ p = 0.520, \ d = 0.35, \ \beta = 17\% \) | \( T_{(16)} = -1.4, \ p = 0.178, \ d = 0.34, \ \beta = 26\% \) |

| Between groups | ACLR vs. Healthy (pre-planned) | ACLR vs. Healthy (unplanned) |
|----------------|--------------------------------|--------------------------------|
| **RP-1**       | \( T_{(1,25)} = 0.7, \ p = 0.50, \ d = 0.26, \ \beta = 10\% \) | \( T_{(1,25)} = -1.2, \ p = 0.246, \ d = 0.48, \ \beta = 21\% \) |
| **RP-2**       | \( T_{(1,25)} = 0.2, \ p = 0.83, \ d = 0.1, \ \beta = 16\% \) | \( T_{(1,25)} = -1.3, \ p = 0.193, \ d = 0.50, \ \beta = 23\% \) |
| **NS**         | \( T_{(1,25)} = 0.2, \ p = 0.85, \ d = 0.06, \ \beta = 10\% \) | \( T_{(1,25)} = 1.3, \ p = 0.279, \ d = 0.42, \ \beta = 18\% \) |

RP-1 = Readiness potential 1 (-1500 to -1000 ms), RP-2 = Readiness potential 2 (-1000 to -500 ms), NS = Negative slope (-500 to 0 ms; movement onset); PP = pre-planned condition, UN = unplanned condition.)
Fig. 1. Example of participants’ Movement-related-cortical potentials (MRCP) at the Cz-electrode of both landing conditions separated into the three successive epochs towards movement onset (RP-1 = Readiness potential 1 (-1500 to -1000 msec), RP-2 = Readiness potential 2 (-1000 to -500 msec), NS = Negative slope (-500 to 0 msec; movement onset); PP = pre-planned condition, UN = unplanned condition).
Fig. 2. Movement-related-cortical potentials (MRCP) for each of the analysed electrodes at all three successive epochs for all participants (RP-1 = Readiness potential 1 (-1500 to -1000 msec), RP-2 = Readiness potential 2 (-1000 to -500 msec), NS = Negative slope (-500 to 0 msec; movement onset); PP = pre-planned condition, UN = unplanned condition).
Fig. 3. Mean Movement-related-cortical potentials (MRCP) at the central midline (CZ) electrode (l) across all three epochs towards movement onset for the ACLR- and control group during both the pre-planned (A) and unplanned (B) landing condition. (RP-1 = Readiness potential 1 (-1500 to -1000 msec), RP-2 = Readiness potential 2 (-1000 to -500 msec), NS = Negative slope (-500 to 0 msec; movement onset); ACLR = anterior cruciate ligament reconstructed group, CI = confidence interval).
Fig. 4. Mean Movement-related-cortical potentials (MRCP) at the central midline (CZ) electrode in comparison of both groups and conditions. From right to left each group: RP-1 = Readiness potential 1 (-1500 to -1000 msec), RP-2 = Readiness potential 2 (-1000 to -500 msec), NS = Negative slope (-500 to 0 msec; movement onset); ACLR = anterior cruciate ligament reconstructed group, PP = pre-planned, UN = unplanned, CI = confidence interval.)
Fig. 5. Frontal theta frequency power at the Fz electrode in comparison between both groups and conditions during the last 500 msec prior movement onset. ACLR = anterior cruciate ligament reconstructed group, PP = pre-planned, UN = unplanned. CI = confidence interval.)
