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Cortical Motor Planning and Biomechanical Stability During Unplanned Jump Landings in Men With Anterior Cruciate Ligament Reconstruction

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Context: Athletes with anterior cruciate ligament (ACL) reconstruction (ACLR) exhibit increased cortical motor planning during simple sensorimotor tasks compared with healthy athletes serving as control groups. This may interfere with proper decision making during time-constrained movements, elevating the reinjury risk.

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

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Ten men with ACLR (age = 28 ± 4 years, time after surgery = 63 ± 35 months) and 17 healthy men (age = 28 ± 4 years) completed 43 ± 4 preplanned (landing leg shown before takeoff) and 51 ± 5 unplanned (visual cue during flight) countermovement jumps with single-legged landings.

Main Outcome Measure(s): Movement-related cortical potentials (MRCPs) and frontal θ frequency power before the jump were analyzed using electroencephalography. Movement-related cortical potentials were subdivided into 3 successive 0.5-second time periods (readiness potential [RP]-1, RP-2, and negative slope [NS]) relative to movement onset, with higher values indicating more motor planning. Theta power was calculated for the last 0.5 second before movement onset, with higher values demonstrating more focused attention. Biomechanical landing stability was measured via peak vertical ground reaction force, time to stabilization, and center of pressure.

Results: Both the ACLR and healthy groups evoked MRCPs at all 3 time periods. During the unplanned task analyzed using *P* values and Cohen *d*, the ACLR group exhibited slightly higher but not different MRCPs, achieving medium effect sizes (RP-1: $P = .25$, $d = 0.44$; RP-2: $P = .20$, $d = 0.53$; NS: $P = .28$, $d = 0.47$). The ACLR group also showed slightly higher θ power values that were not different during the preplanned ($P = .18$, $d = 0.29$) or unplanned ($P = .42$, $d = 0.07$) condition, achieving small effect sizes. The groups did not differ in their biomechanical outcomes (*P* values > .05). No condition × group interactions occurred (*P* values > .05).

Conclusions: Our jump-landing task evoked MRCPs. Although not different between groups, the observed effect sizes provided the first indication that men with ACLR might have consistently relied on more cortical motor planning associated with unplanned jump landings. Confirmatory studies with larger sample sizes are warranted.

Key Words: neurocognition, decision making, electroencephalography, anticipation, agility, anterior cruciate ligament rehabilitation

Key Points

- The jump-landing task evoked a movement-related cortical potential irrespective of group and landing conditions.
- Although the outcomes were not different between groups, the small and medium effect sizes may indicate that men with anterior cruciate ligament reconstruction who have been cleared to return to sport potentially rely on more cortical motor planning associated with unplanned jump landings.
- Confirmatory studies with larger sample sizes and shorter postoperative times are highly warranted to corroborate these initial findings and elucidate their possible implications for secondary injury prevention and return to sport.

Most anterior cruciate ligament (ACL) tears in team sports, such as football or basketball, occur in noncontact situations.[1] In the athlete, surgical reconstruction of the ACL represents a standard procedure aiming to correct the biomechanical function of the ligament.[2] 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) about joint proprioception and movement via ascending pathways.[3,4] The rupture and reconstruction of the torn ligament lead to considerable loss or damage of ACL mechanoreceptors.[5] Despite the replacement of the native ACL using a tendon graft, neurosensory deficits persist,[2] and whether any substantial reinnervation occurs is doubtful.[6] With deficient ACL afferent, proprioceptive, and other somatosensory input, the brain is less able to fine tune movement and mediate joint stability via descending neuromuscular pathways.[3] Neurophysiological evidence has suggested that ACL rupture and the resulting sensory deafferentation are associated with persistent changes in functional brain activation patterns during movement.[7] These neural adaptations may contribute to the frequently observed impairments of motor functions (eg, altered proprioception, postural control, muscle strength, and landing mechanics)[8–10] and high reinjury rates[11] after return to sport in affected individuals.

Specifically, researchers using electroencephalography (EEG) have shown that people with ACL reconstruction (ACLR) exhibited enhanced activity of the frontal or parietal cortex, or both areas, during both passive knee loading via arthrometry[12] and active execution of sensorimotor conditions, such as angle and force reproduction.[13,14] Results from magnetic resonance imaging studies supported this finding, as those with ACL injury demonstrated higher activation in areas of the brain responsible for motor planning, sensory processing, and visual control during isolated knee flexion-extension movements compared with healthy control groups.[15,16] Thus, the brains of those with ACL injury or ACLR seemed to rely more on higher-order attentional control and somatosensory processing to compensate for the neuromechanical decoupling[7] and to maintain task performance.[13] Besides these central nervous system compensation strategies, long-lasting changes in the motor cortex have been identified using transcranial magnetic stimulation.[7,17] Specifically, patients with ACLR exhibited decreased corticomotor excitability of areas responsible for the innervation of the knee muscles.[7]

However, the rather simple and feedback-controlled movement conditions 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.[18] They need to process a multitude of visual stimuli while simultaneously monitoring and spontaneously adjusting their own motor plans and actions to sudden changes. Previous investigators have attempted to mimic the time-constrained decision-making demands in athletic movements by imposing unplanned conditions.[19] During these conditions, a stimulus indicating the requested landing limb or side-cutting direction after a run or jump was displayed only shortly before ground contact. Compared with a preplanned control task (ie, this information was known before the trial began), the unplanned task induced altered landing biomechanics, suggesting a higher risk for noncontact ACL injury.[19] Beyond this, the unplanned task predisposed erroneous decision making (eg, landing on the wrong side).[20]

The cortical processes associated with such sport-related movements are still unclear. One may speculate that participants with ACLR need more brain resources to prepare and initiate unplanned movements compared with healthy individuals (ie, those with 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 reinjury risk. The EEG can provide markers of underlying neurophysiological mechanisms with precise time resolution. Movement-related cortical potentials (MRCPs) and frontal theta (θ) frequency power are valid measures for quantifying motor planning and attentional processes associated with voluntary movements such as jumping.[21,22] The purpose of our study was to compare cortical motor planning, biomechanical landing stability, and decision-making quality in preplanned and unplanned jump landings between participants with ACLR and healthy (control) individuals.

METHODS

Study Design

This cross-sectional exploratory study was performed according to the Guidelines for Good Clinical Practice stated in the Declaration of Helsinki. All participants provided written informed consent, and the local ethics committee approved the study (reference No. 2017/27), which was registered at https://www.ClinicalTrials.gov (NCT03336060). The control group was selected from an earlier trial.[20] All participants received a 1-time payment of €50 (US $56.80).

Participants

Participants were recruited at local physical rehabilitation centers, physiotherapy and medical practices, sports clubs, fitness centers, and the local university campus using flyers, emails, and word of mouth. Inclusion criteria for participants with ACLR and healthy participants were (1) male sex, (2) age between 20 and 40 years, (3) regular sporting activity ($\geq$2 times per week), and (4) countermovement jump (CMJ) height of $\geq$30 cm to ensure sufficient decision-making time during the jump. Participants with ACLR were included if they (1) had a history of unilateral, noncontact ACL injury with reconstruction surgery (>1 year earlier), irrespective of the graft used and surgical procedure; (2) achieved a limb symmetry index in the single-legged hop-for-distance test of >85%; and (3) were cleared for return to sport in a shared-decision process. Exclusion criteria for all participants were (1) severe somatic or psychological disease or disorder, (2) acute or chronic joint or tissue inflammation, (3) intake of drugs modifying pain perception and proprioception, (4) muscle soreness, or (5) a history of brain or head injury (<1 year). Additional exclusion criteria for participants with ACLR were severe concomitant knee injury (ie, grade 3 or 4 bone bruise, full-thickness articular cartilage lesion >1 cm^2, and "unhappy triad" [injury to the ACL, medial collateral ligament, and meniscus]) or a previous ACL injury or surgery of the uninvolved knee. Healthy control participants with a history of severe musculoskeletal injuries (eg, ACL tear) or surgery of the lower limb were excluded.

We only assessed men to avoid the potentially confounding effects of sex on the study outcomes. Female participants exhibited altered landing mechanics and were at higher risk of sustaining a knee injury.[23] As a result, ACL injury mechanisms have been primarily explored in female athletes, and any male-specific injury risk factors needed to be considered.[24] Furthermore, it was easier for male participants to achieve the required jump height of approximately 30 cm in the CMJ (see the "Jump-Landing Task" section).

We determined the sample size using the means and SDs reported in a previous EEG comparison[13] of mean frontal θ frequency power during a sensorimotor task between participants with ACLR and healthy participants. The a priori sample size calculation using a 2-tailed α of 0.05 and β of 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 2 days within 1 week (≥3 days in between the 2 days) at comparable times of day. During visit 1, we familiarized the participants with the jump-landing task. During this session, we instructed participants to rate their level of fear of (re)injury under the unplanned condition. Additionally, data regarding anthropometrics, physical activity, neuromuscular performance, and self-reported knee function were assessed for all participants. For those with ACLR, we documented the time since surgery. Visit 2 consisted of the actual measurements (jump-landing task). Data collection was conducted under standardized circumstances (room size, temperature, humidity, workplace, and lighting).

Jump-Landing Task

All participants performed repeated CMJs with planned versus unplanned single-legged landings on a capacitive pressure plate (model FDM; zebris Medical GmbH) with a sampling rate of 50 Hz and error of measurement of ≤5%. For both landing conditions, participants were required to produce flight times of about 500 milliseconds (corresponding to a jump height of about 30 cm), resulting in available response times of approximately 380 milliseconds during the jump in the unplanned condition, which is in line with earlier work.[19] All participants practiced generating these flight times during the familiarization session (day 1).

In the preplanned task, participants received the visual cue depicting the requested landing limb (left or right footprint displayed on a presentation slide [PowerPoint 2010; Microsoft Corp] on a 17-in (43.2-cm) laptop screen, 2.5 m in front of them) before the jump. In the unplanned task, this information was shown only on takeoff (120-millisecond delay after leaving the ground).

For both conditions, at least 40 valid trials were performed. To avoid exhausting participants, we divided the jumps into 6 to 7 blocks, depending on the success rate of landings, of 14 jumps with a 5-minute rest in a seated position between blocks. Given that the rate of successful landings was higher during the preplanned trials, the preplanned: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 (version 11.06; University of Frankfurt).

Before each jump, participants were instructed to stand with the feet hip-width apart, the knees slightly flexed, and the hands at the hips. They were then orally informed about the upcoming landing condition according to the randomization list. At this moment, we asked participants to mentally prepare for the upcoming jump landing for at least 3 seconds (measured using a stopwatch, which was not seen by participants) before initiating movement. We used this period to guarantee sufficient premovement planning time. Participants were asked to stabilize as soon as possible after landing and maintain a stable stance for 10 seconds while focusing on a cross mounted to the wall at eye level. Further details regarding the setup of the jump-landing task have been described elsewhere.[25]

Primary Outcome: EEG Set-Up and MRCP and Frontal θ Frequency Power Acquisition

The cortical activity before the jumps was measured using a 32-channel EEG system with a sampling rate of 500 Hz, a 24-bit analog-to-digital converter, and a wireless amplifier (model LiveAmp; Brain Products). An integrated 3-axis acceleration sensor with a measurement range of ±2*g*, 12-bit resolution of 1 mg/bit, and error of ±200*g* carried in a custom-made backpack with a total weight of 700 g was attached to the upper back of the participants. The active slim electrodes were embedded in the EEG cap (model actiCAP; EASYCAP GmbH) according to the international 10–20 system. Impedance was kept <5 kΩ, and no online filters were applied. We used the FCz electrode as reference. The EEG was continuously recorded throughout the jump-landing task. The EEG data were filtered using a high-pass Butterworth filter at 0.001 Hz (24 dB/octave) and a low-pass Butterworth filter at 40 Hz (24 dB/octave). For each trial, we segmented the EEG signals into intervals of 2500 milliseconds, from 2000 milliseconds before to 500 milliseconds after movement onset (jump).

For movement onset detection, we used the acceleration data, which were 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 of the BrainVision Analyzer (Brain Products GmbH) software with a level trigger threshold of –7 μV. If this threshold was not appropriate, we manually adjusted the onset time to the time when the vertical acceleration exceeded the average of the previous level by 2 SDs. Trials were eliminated from analyses if the movement onset was not clearly detectable (eg, very slow movement or cancellation of an initiated movement), the standing time before the initiation of the jump was too short (<3 seconds), or both.

The MRCP was a low-frequency, slowly increasing negative potential, which began up to 2 seconds before voluntary movements.[21] The MRCP represents the cortical processes associated with the planning and preparation of movements, such as a jump.[21] Greater negativity indicates more neurocognitive involvement associated with the movement planning and preparation and vice versa.[21] According to Spring et al,[26] the MRCP can be divided chronologically into the following periods relative to movement initiation (onset = 0 milliseconds): readiness potential 1 (RP-1 = –1500 to –1000 milliseconds), readiness potential 2 (RP-2 = –1000 to –500 milliseconds), and negative slope (NS = –500 to 0 milliseconds; Figure 1).[21] The nonlateralized readiness potentials reflected the rather unconscious movement-related decision-making processes of the presupplementary and supplementary motor cortex. The steeper NS potential corresponded to the conscious movement preparation processes of side-specific body movements and occurred in the contralateral primary motor cortex.[21] The mean activity of the MRCP was calculated for the frontocentral (FC1 and FC2) and central electrodes (C3, Cz, and C4), as these channels were

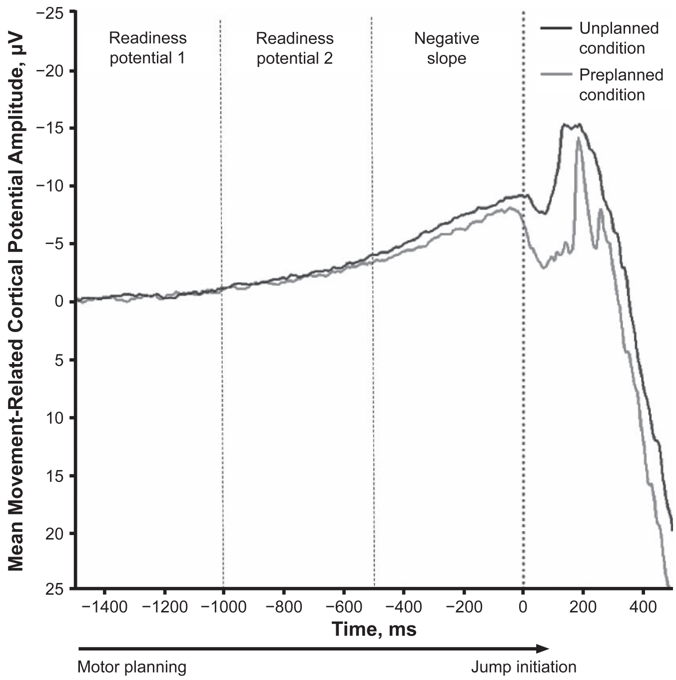

Figure 1. Example of participants' movement-related cortical potentials at the central midline electrode of both landing conditions separated into the 3 successive periods toward movement onset (0 ms): readiness potential 1 (–1500 to –1000 ms), readiness potential 2 (–1000 to –500 ms), and negative slope (–500 to 0 ms).

located above the supplementary and primary motor areas. To examine if our jump-landing task evoked an MRCP, we calculated the mean values and 95% CIs of the preplanned and unplanned conditions for these electrodes at each time period, regardless of group. The criteria for MRCP were fulfilled if the level of negativity reached a statistical difference (based on the 95% CI). 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 θ power spectrum (4–7 Hz), we used the fast Fourier transformation. The θ frequency power was most prominent over the midline frontocentral electrodes. It was generated in the anterior cingulate cortex, which is thought to be part of the human executive attentional system.[27] Greater frontal θ activity was related to a higher level of focused attention.[28] Previous researchers demonstrated its sensitivity for the attentional demands associated with the motor planning of athletic movements, such as preplanned jump and side-stepping maneuvers.[22,29] According to Burcal et al,[29] frontal θ frequency power was calculated for the last 0.5 second 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, before each jump, participants were instructed to stand in a quiet and relaxed position while visually fixating on the cross on a screen in front of them to minimize horizontal eye movements and eye blinks. This position had to be maintained until visual inspection of the EEG channels indicated clean data recording and impedance <5 kΩ.

To remove nonstereotypical artefacts (eg, low frequency drifts and offsets due to movement, sweating, horizontal eye movements), we conducted an individual-based semiautomatic independent component analysis (ICA) by filtering the data using a higher cutoff for the high-pass frequency (1 Hz). The resulting ICA matrix (with excluded nonstereotypical 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[30]) enabled us to clearly identify eye blinks, which we manually removed using ocular correction ICA (FP2 electrode versus common reference). Additionally, we conducted an automated artefact rejection to remove potentially remaining artefacts according to the criteria used by Saliasi et al.[31] Based on a final visual inspection, only artefact-free trials were used for analysis.

Secondary Outcome: Biomechanical Stability and Decision-Making Quality

The capacitive pressure measurement platform 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-legged stance was maintained without touching the ground using the free limb, leaving the force plate, or touching the ground with the hands for at least 10 seconds. We measured 3 biomechanical variables: (1) peak vertical ground reaction force (pVGRF) at landing, (2) center-of-pressure path length (first 2.5 seconds upon landing), and (3) time to stabilization (TTS; estimated relative to the whole standing period of 10 seconds after landing). Additionally, we collected the number of *standing errors* (ie, landing on the correct limb but touching the pressure plate with the free limb or hands or leaving the platform). As a measure of decision-making quality, the number of decision errors (ie, landing with wrong foot or both feet) was documented. For more details of these outcomes, please refer to Giesche et al.[25]

To examine the comparability between groups, we assessed the following additional variables during visit 1 of all participants: anthropometrics (body weight, height, and body mass index), physical activity (metabolic equivalents per hour) during the previous week using the International Physical Activity Questionnaire short form, and the number of participants who were engaged in team sports games at least once each week. Neuromuscular function was operationalized by the maximum CMJ height (with hands at hip, highest jump out of 3 trials) and single-legged hop for the *distance limb symmetry index* (the longest distance jumped per limb out of 3 trials).[32] Self-reported knee function of the ACLR knee and the knees of healthy participants was measured using the Lysholm Knee Scoring Scale.[33] Task-specific fear of movement or reinjury during the unplanned activity was evaluated during the familiarization session using a 10-cm visual analog scale (0 cm = *very low*, 10 cm = *very highly pronounced*). Self-reported levels of alertness, as well as fatigue of the lower limb (before, in the middle of, and after the jump-landing task; the mean of all 3 time points), were measured during the actual jump-landing task on visit 2 using the same 10-cm visual analog scale. We characterized such self-reported

Table 1. Group Characteristics

Characteristic	Group (n)		P Value
	Control (17)	Anterior Cruciate Ligament Reconstruction (10)	
	Mean ± SD (Minimum–Maximum)[a]		
Age, y	28 ± 4 (22–38)	28 ± 4 (20–32)	.96
Height, cm	182 ± 6 (171–194)	183 ± 3 (178–188)	.85
Mass, kg	82 ± 11 (63–106)	87 ± 8 (78–101)	.21
Time since surgery, mo	NA	63 ± 35 (28–140)	NA
Physical activity, metabolic equivalents/h	70 ± 47 (23–175)	63 ± 54 (4–172)	.73
Team game sports (minimum once per week),[b] n/N (%)[c]	6/15 (40)	4/8 (50)	.69
Explosive strength lower limb (countermovement jump height), cm	40 ± 6 (30–51)	36 ± 5 (30–45)	.12
Limb symmetry single-legged hop for distance, %	96 ± 3 (1–11)	96 ± 4 (1–2)	.88
Lysholm Knee Scoring Scale score[b]	98 ± 3 (90–100)	89 ± 8 (76–100)	.01
Fear of (re)injury (unplanned condition), visual analog scale[b,d]	2 ± 2 (0–8)	2 ± 2 (0–7)	.96
Self-reported level of attention, visual analog scale[e]	8 ± 1 (5–10)	7 ± 2.4 (3–10)	.19
Self-reported level of fatigue, visual analog scale[e]	3 ± 2 (0–7)	5 ± 3 (1–8)	.33
Flight time, planned vs unplanned condition, ms	472 ± 23 (411–499) vs 483 ± 27 (414–515)[d]	457 ± 28 (412–496) vs 469 ± 29 (421–507)[d]	.76

Abbreviation: NA, not applicable.

[a] Unless otherwise noted.

[b] Nonnormally distributed data.

[c] Number of group participants/total number participants (%).

[d] $P < .05$.

[e] Visual analog scale ranged from 0 cm (*very low*) to 10 cm (*very highly pronounced*).

outcomes because they might have influenced both premovement cortical activity and biomechanical landing stability. Finally, we assessed the flight time of each jump-landing trial because this variable corresponded to the available response time during the jump. Shorter flight times were associated with less decision-making quality during the unplanned task.[20]

Statistical Analysis

Before performing the analyses, we examined the underlying assumptions for parametric and nonparametric testing. Descriptive reporting included means or medians, SDs, and 95% CIs.

The cortical correlates of motor planning were compared (1) within groups (between the preplanned and unplanned conditions) using the dependent *t* test or the Wilcoxon signed rank test and (2) between groups (within conditions) using the independent *t* test or the Mann-Whitney *U* test. To test for possible condition × group interaction effects, we compared the between-conditions differences between groups again using the independent *t* test or the Mann-Whitney *U* test. The same procedure was followed for the biomechanical outcomes. Regarding the standing and decision errors, the relative error count in percentage was calculated; within- and between-groups analyses were conducted by applying nonparametric statistical tests.

To investigate the effects of limb on both the cortical activity and biomechanical outcomes of both conditions in the ACLR group, we compared the individual variables between the operated and unaffected limbs. Between groups, we compared the ACLR and the healthy control group's dominant limb. If side differences were observed within or between groups, we adopted the analyses mentioned earlier by matching the ACLR with the dominant limb of the healthy participants and vice versa. If no differences were observed, we performed the statistical analyses based on the average values of both limbs combined for each group. As a supplement to significance testing using the *P* value, we calculated effect sizes (Cohen *d*), which were interpreted as *small* (d = 0.2), *medium* (d = 0.5), or *large* (d = 0.8),[34] to estimate and interpret the within- and between-conditions differences regardless of sample size.[35] Additionally, we calculated the post hoc β power for the MRCP comparisons within and between groups. Given the small sample size, we conducted no cofactor analyses.

The α error was set at 5%. All statistical analyses were performed using SPSS (version 24; IBM Corp) and Excel (version 2016; Microsoft Corp). Cohen *d* effect sizes and β power were determined using G*Power (version 3.1.9.2; University of Düsseldorf). All EEG data processing was conducted using the BrainVision Analyzer software.

RESULTS

Ten participants with ACLR and 17 healthy individuals completed the jump-landing task; none withdrew consent, and none was excluded. We found no differences in participant characteristics between groups apart from self-reported knee function, which was lower in the participants with ACLR than in the healthy participants ($P = .01$; Table 1). In both groups, the unplanned condition resulted in longer flight times than the preplanned condition ($P < .05$). However, the flight times of both conditions were not different between groups ($P = .76$; Table 1).

In both, the cortical and biomechanical measures did not differ between the ACLR and unaffected limbs ($P > .05$). The measures also did not differ between the ACLR group and the dominant limb of the healthy group ($P > .05$).

Both groups performed a comparable total number of preplanned (ACLR group = 43 ± 4, healthy group = 42 ± 3) and unplanned (ACLR group = 50 ± 7, healthy group =

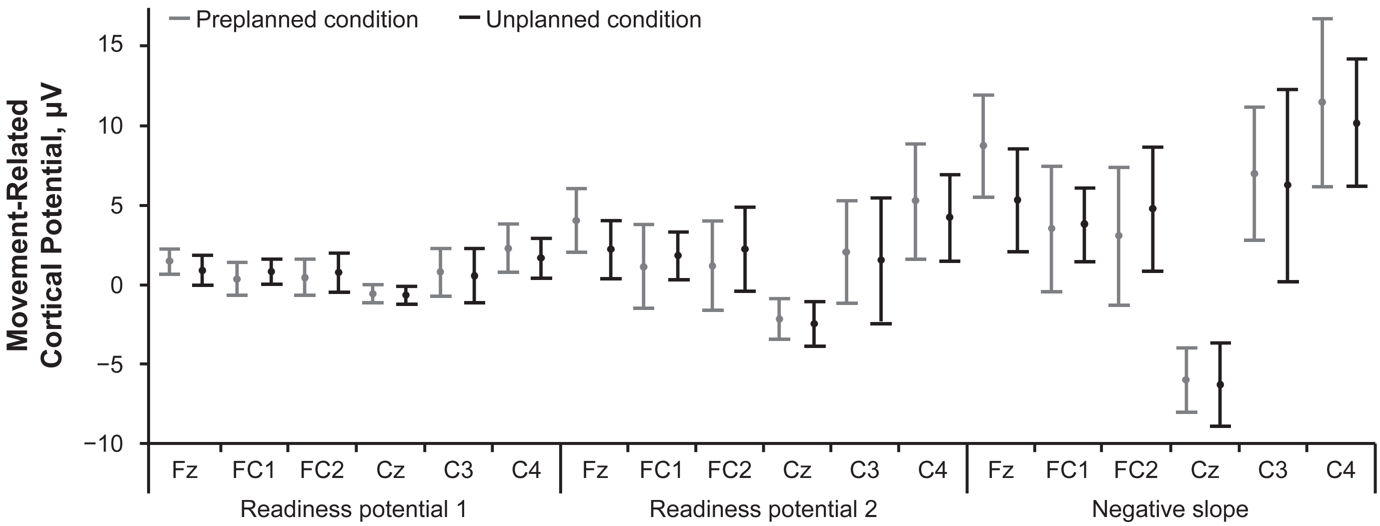

Figure 2. Mean (95% CI) movement-related cortical potentials for each analyzed electrode at all 3 successive time periods for all participants. Readiness potential 1 is the period from –1500 to –1000 ms; readiness potential 2, from –1000 to –500 ms; and negative slope, from –500 to 0 ms (movement onset). Abbreviations: C, central; Cz, central midline; FC, frontocentral; Fz, frontal midline.

51 ± 5) jump landings. The number of successful trials for both the preplanned (ACLR group = 43 ± 4, healthy group = 42 ± 3) and unplanned conditions (ACLR group = 36 ± 6, healthy group = 37 ± 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 for the preplanned and unplanned conditions. The corresponding trials were also removed from the biomechanical analysis. For the preplanned task, we used 35 ± 8 for the ACLR group and 35 ± 5 for the healthy group. For the unplanned task, we used 29 ± 9 for the ACLR group and 32 ± 6 for the healthy group.

Cortical Correlates of Motor Planning

Both the preplanned and unplanned conditions evoked an MRCP at all time periods regardless of group (Figure 1). The cortical potential was detected at the central midline (Cz) electrode only (Figure 2).

Compared with the preplanned activity, the unplanned task resulted in MRCP values that were slightly higher but not different for the ACLR group (RP-1 = 28%, $P > .05$; RP-2 = 81%, $P > .05$; NS = 38%; $P > .05$) and similar values for the healthy group (RP-1 = –12%, $P > .05$; RP-2 = –25%, $P > .05$; NS = –17%, $P > .05$; Table 2; Figure 3). Between-groups comparison indicated slightly higher values for the ACLR group than the healthy group during the unplanned task, which again were not different (RP-1 = 269%, $P > .05$; RP-2 = 101%, $P > .05$; NS = 53%, $P > .05$; Table 2; Figure 4). During the preplanned activity, both groups produced similar but not different MRCPs ($P > .05$; Table 2; Figure 5). No condition × group interaction effects occurred (RP-1: $P = .68$, $d = 0.16$; RP-2: $P = .21$, $d = 0.51$; NS: $P = .38$, $d = 0.46$).

For frontal θ frequency power, no differences were found between conditions within groups ($P > .05$; Figure 5). The ACLR group again produced slightly higher values that were not different compared with the healthy participants for the preplanned (25%; $Z_{1,25} = 1.4$, $P = .18$, $d = 0.29$, $\beta = 25\%$) and unplanned conditions (8%; $Z_{1,25} = 0.8$, $P = .42$, $d = 0.07$, $\beta = 11\%$; Figure 5). No condition × group interaction effects occurred ($P = .36$).

Biomechanical Landing Stability and Decision-Making Quality

In both groups, the unplanned task resulted in higher center-of-pressure (ACLR group = 22%, $t_9 = 3.5$, $P = .007$,

Table 2. Inference Statistic Results of Within- and Between-Group Comparisons for Movement-Related Cortical Potentials (MRCPs) at the Central Midline (Cz) Electrode

	Within-Group Comparison								Between-Groups Comparison							
	ACLR Group (Preplanned vs Unplanned Task)				Healthy Group (Preplanned vs Unplanned Task)				ACLR vs Healthy Group (Preplanned Task)				ACLR vs Healthy Group (Unplanned Task)			
Movement-Related Cortical Potentials	t_9	*P* Value	Cohen *d*	β, %	t_{16}	*P* Value	Cohen *d*	β, %	t_{25}	*P* Value	Cohen *d*	β, %	t_{25}	*P* Value	Cohen *d*	β, %
Readiness potential 1[a]	0.3	.78	0.09	7	−0.2	.83	−0.05	5	0.7	.50	0.27	10	1.2	.25	0.44	21
Readiness potential 2[b]	0.8	.44	0.25	19	−1.1	.29	−0.26	14	−0.2	.83	−0.09	16	1.3	.20	0.53	23
Negative slope[c]	0.7	.52	0.21	17	−1.4	.18	−0.34	26	−0.2	.85	−0.08	10	1.1	.28	0.47	18

Abbreviation: ACLR, anterior cruciate ligament reconstruction.

[a] –1500 to –1000 ms.

[b] –1000 to –500 ms.

[c] –500 to 0 ms (movement onset).

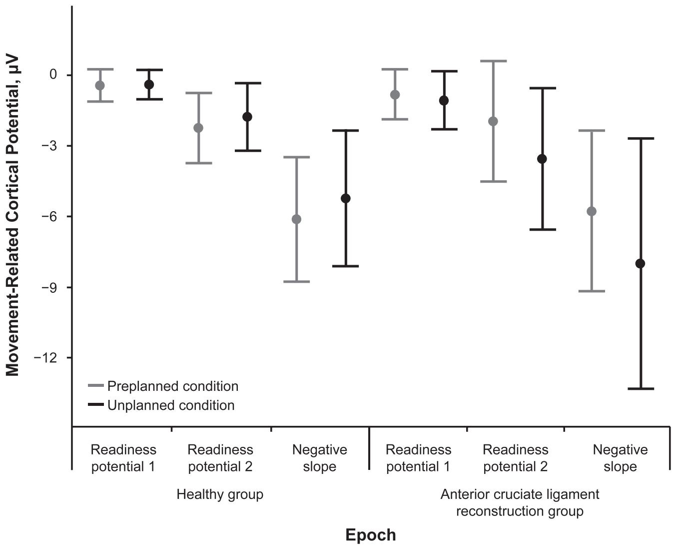

Figure 3. Mean (95% CI) movement-related cortical potentials at the central midline Cz electrode with both groups and conditions. Readiness potential 1 is the period from –1500 to –1000 ms; readiness potential 2, from –1000 to –500 ms; and negative slope, from –500 to 0 ms (movement onset).

$d = 1.1$; healthy group = 13%, $t_{16} = 3.9$, $P < .01$, $d = 0.95$) and standing error rates, reaching moderate-to-large effect sizes (ACLR group = 5%, $Z_9 = –2.4$, $P = .02$, $d = 0.57$; healthy group = 4%, $Z_{16} = –3.2$, $P = .001$, $d = 0.98$). However, between groups, the variables did not differ within or between conditions ($P > .05$). Within groups, no between-conditions differences were noted for TTS (ACLR: $t_9 = –1.7$, $P = .12$, $d = –0.54$; healthy participants: $t_{16} = –1.5$, $P = .15$, $d = –0.37$) and pVGRF (ACLR group: $t_9 = 1.3$, $P = .22$, $d = 0.42$; healthy group: $t_{16} = 0.94$, $P = .36$, $d = 0.23$). Between groups, the variables did not differ within or between conditions ($P > .05$).

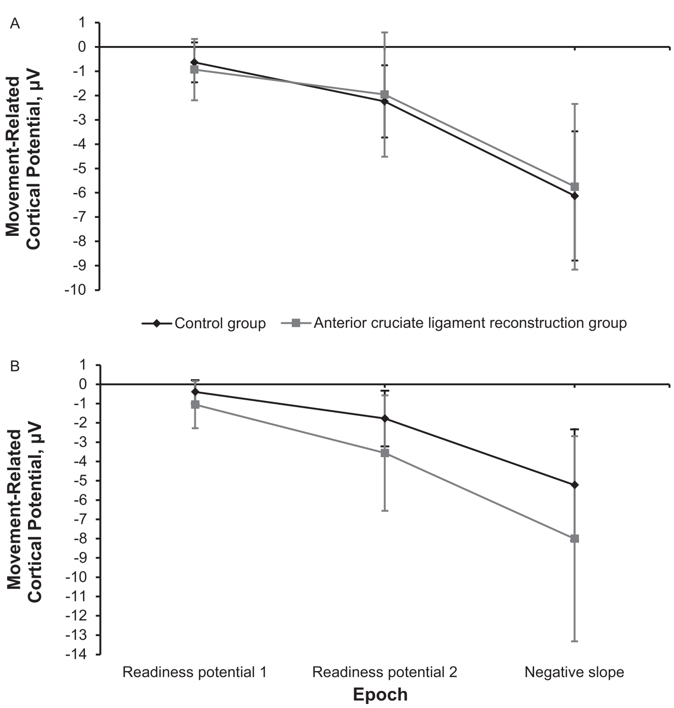

Figure 4. Mean (95% CI) movement-related cortical potentials at the central midline electrode across all 3 time periods toward movement onset (0 ms) for the anterior cruciate ligament reconstruction and control groups during the A (preplanned) and B (unplanned) landing conditions. Readiness potential 1 is the period from –1500 to –1000 ms; readiness potential 2, from –1000 to –500 ms; and negative slope, from –500 to 0 ms.

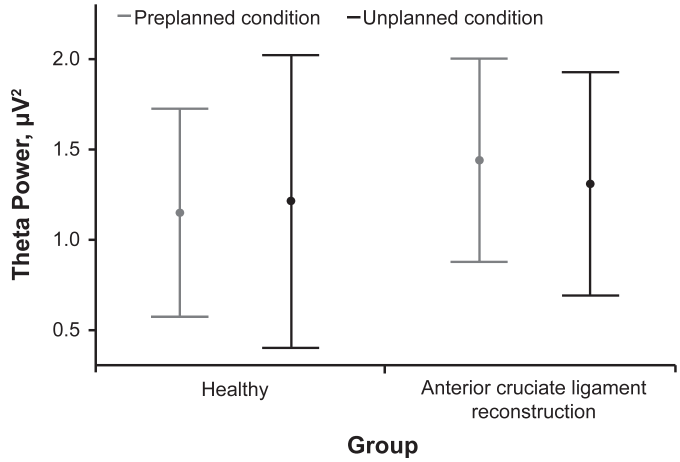

Figure 5. Mean (95% CI) frontal θ frequency power at the frontal midline electrode between both groups and conditions during the last 500 ms before movement onset.

Regarding decision-making quality, both groups produced higher decision error rates during the unplanned than the preplanned task (ACLR group = 22% versus 0%, $Z_9 = –2.8$, $P = .005$; healthy group = 19% versus 0%, $Z_{16} = –3.5$, $P < .001$). The decision error rate was not different between groups ($P > .05$).

DISCUSSION

Our goal was to investigate the cortical motor-planning processes associated with unplanned athletic movements in individuals with ACLR. Our jump-landing task evoked an MRCP irrespective of group and landing condition. In contrast to our assumption, the brains of participants with ACLR did not rely on a higher level of cortical motor planning and attention to initiate unplanned movements compared with the brains of healthy participants. The groups did not differ in terms of the assessed biomechanical landing stability or decision-making quality measures and were similar across all characteristics except self-reported knee function.

Cortical Correlates of Motor Planning

At first glance, our finding of no difference in cortical activity between the participants with ACLR and the healthy participants contrasted with previous evidence. Authors of EEG and functional magnetic resonance imaging studies observed that individuals with ACLR or injury exhibited changes in functional brain activation patterns during sensorimotor tasks, such as joint repositioning[13] and knee-flexion and -extension movements.[16] According to the neuroplasticity hypothesis, these neural changes (eg, increased motor planning and focused attention) were interpreted as adaptation strategies of the central nervous system to compensate for the trauma-induced sensory deafferentation and aimed at maintaining motor-task performance.[7] Contrary to these investigators, we assessed cortical activity before movement initiation and not during motor-task executions. Compared with the latter, standing in a stable position during the motor preparation period did not rely on excessive sensory input from the knee joint.

However, although not different, MRCPs during the unplanned task still tended to be slightly higher (with small-to-moderate effect sizes) in the participants with ACLR than in the healthy participants. This occurred throughout all 3 time periods. Therefore, it appeared that the brains of individuals with ACLR may have required more activity for both the unconscious (presupplementary and supplementary motor cortex; RP-1, RP-2) and the conscious (primary motor cortex; NS)[21] motor planning associated with the jump.

This trend may have been partially explained by persistent reductions in corticomotor excitability demonstrated in individuals with ACLR.[17] This would suggest that those individuals required a greater stimulus to excite the descending cortical pathways (ie, higher motor threshold) innervating the knee muscles and initiate the movement.[17] Another explanation for the higher MRCPs of the ACLR group may have been the perceived task demands by the participants. In unplanned landings, the knee was exposed to higher loads, as time was insufficient for feed-forward planning of the landing.[19] Participants with ACLR may have perceived the unplanned task as more challenging because they had less confidence in loading the operated knee if its function was not completely restored, as indicated by a lower Lysholm score. This possibly led to an increase in the motor thresholds because a higher level of internal resistance had to be overcome. This interpretation is consistent with the findings of a previous EEG study[36] showing that the initiation of a challenging movement, such as a bungee jump, results in higher MRCPs compared with rather easy and safe movements (eg, finger movements) because less effort is needed to overcome the inner resistance to start the latter.

The MRCPs associated with our task occurred at the central midline (Cz) electrode only, regardless of condition, time period, or group. These potentials reflected the conscious intention to move and occurred in the primary motor cortex contralateral to the moved body side.[21] Given the somatotopic organization of the cortex, we initially included the lateral electrodes C4 and C3, but the lower extremities were represented in the middle of the motor cortex (midline)[37] and so we did not find a laterality effect.

The ACLR group tended to exhibit higher premovement frontal θ frequency power values (small-to-medium effect sizes) than the healthy participants. Thus, the affected individuals seemed to direct more attentional resources to the jump. It was possibly more physically demanding for them to achieve the required jump height throughout the jump-landing task if they had persistent postoperative strength and self-reported knee function deficits.

Nevertheless, the within- and between-groups comparisons were not different. These findings may be attributable to the small sample size (eg, low post hoc β power) and large amount of heterogeneity. The participants with ACLR varied in time since surgery (28–140 months) and self-reported knee function (76% to 100%), which may have contributed to findings that were not different. On the other hand, the 2 groups were comparable across a range of characteristics, which may have made it more difficult to detect small effects or differences between groups in cortical activity. Higher-powered confirmatory studies are warranted to assess statistical differences. Another potential reason for the lack of differences in cortical activity may have been that both groups performed the jump-landing task similarly in terms of jump height, decision-making quality, and biomechanical landing stability. Future work including an ACLR group with more neuromuscular impairments may result in differences in cortical activities.

Biomechanical Landing Stability and Decision-Making Quality

The observed biomechanical landing safety and decision-making quality decrements during the unplanned versus the preplanned condition were in line with those reported by previous researchers.[19,20] These task performance decrements were most likely the result of the time constraints that made it difficult to prepare the landing properly during the jump.[19] We did not find that the ACLR group displayed greater performance decrements in biomechanical landing safety and decision-making quality compared with the healthy group. This is not consistent with earlier results that indicated different landing mechanics in participants with ACLR associated with possibly greater knee loading during both preplanned[38,39] and unplanned movements.[40] Besides insufficient statistical power, the lack of between-groups differences may have reflected the relatively long postoperative timeframe and the high level of neuromuscular restoration. This may also explain why we did not observe differences between the ACLR and uninjured limbs in any of the assessed outcomes. Niederer et al[41] observed that unplanned biomechanical jump-landing deficits in the ACLR limb persisted 18 to 26 months after surgery. This period fits the proposed time of high risk for a subsequent ACL injury after ACLR and return to sport. Future studies should therefore be done to replicate our approach, considering this critical postoperative period.

Limitations

Our study had limitations. First, the statistical power of this exploratory study was too low to detect between-groups differences. Second, because of the small sample size, we did not account for possible confounders, such as jump height, self-reported knee function, level of expertise, or type of sport (open- versus closed-skill sports),[18] which may have affected task performance. For example, one may speculate that open-skill athletes (eg, football and basketball players) who interact in highly variable and unpredictable environments are more used to the demands associated with the unplanned condition than closed-skill athletes (eg, runners) interacting in more consistent, predictable, and self-paced environments. Third, the findings only reflect men who were capable of reaching a minimum height of 30 cm in the CMJ. Fourth, although we asked participants to respond to the visual cue on takeoff, we cannot exclude the possibility that some may have guessed the landing side or followed their predefined motor plans, regardless of the presented stimuli. Fifth, relative to the preplanned condition, the unplanned task resulted in more unsuccessful trials. Thus, a larger total number of unplanned trials was necessary to reach the predefined minimum number of successful trials for both conditions. Hence, participants with a higher landing or standing error rate were required to complete a larger number of trials, which may have predisposed some of them to fatigue or learning effects. Sixth, given excessive movement artefacts associated with the jump, the analysis of 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 by the brain. Our results should encourage scientists to investigate these neurocognitive processes during challenging athletic tasks, such as unplanned jump landings, by using mobile brain and body imaging methods.[42]

Practical Implications and Clinical Take-Home Messages

- Although no differences were observed, our work provides the first indications that male athletes with ACLR who have been cleared to return to sport may still need more cortical motor planning for unplanned jump landings.
- Future confirmatory studies with larger sample sizes, shorter postoperative timeframes, and both sexes are warranted to verify this and elucidate potential implications for secondary injury prevention and return to sport.
- Unplanned jump landings resulted in less biomechanical landing stability and predisposed participants to 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 tasks or similar jump-landing tasks to screen and train their athletes.

CONCLUSIONS

Our jump-landing task evoked an MRCP irrespective of the group and landing condition. Although the outcomes were not different between groups, the small and medium effect sizes may provide the first indications that men with ACLR who have been cleared to return to sport may rely on more cortical motor planning for unplanned jump landings. Confirmatory studies with larger sample sizes and shorter postoperative timeframes are warranted to corroborate these initial indications and elucidate their potential implications for secondary injury prevention and return to sport.

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